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TECHNICAL REPORT

High Energy Density Polymer Film Capacitors

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14. ABSTRACT

High-energy-density capacitors that are compact and light-weight are extremely valuable in a number of critical DoD systems that include portable field equipment, pulsed lasers, detection equipment, and electromagnetic weaponry. Commercial applications in need of high-power sources are also numerous. We can cite: high intensity flash lamps, defibrillators, lasers, and portable field generators. Applications that require high voltage, short pulse length and high rep rates are limited to low loss dielectrics such as polypropylene. Lower rep rate applications can be served with higher loss dielectrics that include polyester (PET), polyphenylene sulfide (PPS), polyethylene naphthalene (PEN) and polyvinylidene difluoride (PVDF).

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CONVERSION TABLE

Conversion Factors for U.S. Customary to metric (SI) units of measurement.

MULTIPLY → BY → TO GET
TO GET ← BY ← DIVIDE

angstrom	1.000 000 x E -10	meters (m)
atmosphere (normal)	1.013 25 x E +2	kilo pascal (kPa)
bar	1.000 000 x E +2	kilo pascal (kPa)
barn	1.000 000 x E -28	meter^2 (m^2)
British thermal unit (thermochemical)	1.054 350 x E +3	joule (J)
calorie (thermochemical)	4.184 000	joule (J)
cal (thermochemical/cm^2)	4.184 000 x E -2	mega joule/m^2 (MJ/m^2)
curie	3.700 000 x E +1	*giga bacquerel (GBq)
degree (angle)	1.745 329 x E -2	radian (rad)
degree Fahrenheit	$t_k = (t^o f + 459.67)/1.8$	degree kelvin (K)
electron volt	1.602 19 x E -19	joule (J)
erg	1.000 000 x E -7	joule (J)
erg/second	1.000 000 x E -7	watt (W)
foot	3.048 000 x E -1	meter (m)
foot-pound-force	1.355 818	joule (J)
gallon (U.S. liquid)	3.785 412 x E -3	meter^3 (m^3)
inch	2.540 000 x E -2	meter (m)
jerk	1.000 000 x E +9	joule (J)
joule/kilogram (J/kg) radiation dose absorbed	1.000 000	Gray (Gy)
kilotons	4.183	terajoules
kip (1000 lbf)	4.448 222 x E +3	newton (N)
kip/inch^2 (ksi)	6.894 757 x E +3	kilo pascal (kPa)
ktap	1.000 000 x E +2	newton-second/m^2 (N-s/m^2)
micron	1.000 000 x E -6	meter (m)
mil	2.540 000 x E -5	meter (m)
mile (international)	1.609 344 x E +3	meter (m)
ounce	2.834 952 x E -2	kilogram (kg)
pound-force (lbs avoirdupois)	4.448 222	newton (N)
pound-force inch	1.129 848 x E -1	newton-meter (N-m)
pound-force/inch	1.751 268 x E +2	newton/meter (N/m)
pound-force/foot^2	4.788 026 x E -2	kilo pascal (kPa)
pound-force/inch^2 (psi)	6.894 757	kilo pascal (kPa)
pound-mass (lbm avoirdupois)	4.535 924 x E -1	kilogram (kg)
pound-mass-foot^2 (moment of inertia)	4.214 011 x E -2	kilogram-meter^2 (kg-m^2)
pound-mass/foot^3	1.601 846 x E +1	kilogram-meter^3 (kg/m^3)
rad (radiation dose absorbed)	1.000 000 x E -2	**Gray (Gy)
roentgen	2.579 760 x E -4	coulomb/kilogram (C/kg)
shake	1.000 000 x E -8	second (s)
slug	1.459 390 x E +1	kilogram (kg)
torr (mm Hg, 0^0 C)	1.333 22 x E -1	kilo pascal (kPa)

*The bacquerel (Bq) is the SI unit of radioactivity; 1 Bq = 1 event/s.
**The Gray (GY) is the SI unit of absorbed radiation.

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SUMMARY

BACKGROUND

High-energy-density capacitors that are compact and light-weight are extremely valuable in a number of critical DoD systems that include portable field equipment, pulsed lasers, detection equipment, and electromagnetic weaponry. Commercial applications in need of high-power sources are also numerous. We can cite: high intensity flash lamps, defibrillators, lasers, and portable field generators.

Applications that require high voltage, short pulse length and high rep rates are limited to low loss dielectrics such as polypropylene. Lower rep rate applications can be served with higher loss dielectrics that include polyester (PET), polyphenylene sulfide (PPS), polyethylene naphthalene (PEN) and polyvinylidene difluoride (PVDF).

PVDF is the highest energy density polymer dielectric. In the past PVDF was used in a few commercial applications which involved mostly portable equipment such as defibrillators and portable pulse generators. Escalating price of the PVDF polymer film, combined with some severe drawbacks such as high dielectric absorption, resulted in low market demand for PVDF capacitors.

Sigma Technologies proposed to develop a new hybrid PVDF film with superior thermal and mechanical properties that will improve capacitor energy density storage and output efficiency. In Phase I , an acrylate-PVDF hybrid film was produced using a patented, ultra high speed, vacuum polymer deposition process. The acrylate polymer films are formed by vapor deposition of multifunctional acrylate monomers that are deposited on the PVDF as a thin liquid film and are cross linked using electron radiation.

The capacitors were evaluated under a variety of tests and their performance was compared to control parts. The results of this investigation clearly demonstrated that PVDF film properties can be altered significantly with an acrylate coating to allow the production of dry metallized capacitors.

Phase I capacitors produced with hybrid 8□m PVDF/0.5-1.0□m of acrylate film were able to reach voltages over 3000V, while control capacitors with 8□m PVDF did not exceed 1200V. This represents a higher than 7:1 difference in energy density between the two different capacitor designs.

Also preliminary work by Sigma with hybrid PET/Acrylate films has demonstrated that capacitors with energy densities in the neighborhood of 1J/cc can be made, and perhaps higher densities can be obtained with film design optimization. Such capacitors may be more appropriate for higher frequency applications, such as invertors and pulse modulators. Furthermore, three years ago Sigma demonstrated that hybrid metallized polypropylene/acrylate film capacitors can have higher current carrying capability and superior resistance to corrosion and corona discharges. These and other results created such an interest in the Acrylate hybrid films, that all three major capacitor film

manufacturers have now licensed the Acrylate coating technology, and are at different stages of incorporating this technology in their products for AC capacitor films

The above elements very much direct the focus of the Phase II effort. Sigma proposed to increase further the energy density by introducing 2 major concepts:

1. Electrode segmentation
2. Inline control of electrode resistivity using optical means

PHASE II MAIN ACCOMPLISHMENTS AND FINDINGS

The phase II effort focused on optimizing the monomer formulation process, in-situ control of electrode resistivity, machine design, and electrode segmentation. The major accomplishments can be summarized as follows.

Design high dielectric constant monomers

Sigma was successful in the formulation of very high dielectric constant polymeric materials. The highest dielectric constant obtained was **30.67,** which that of a cyano-acrylate monomer.

Heavy Edge Mask and Segmented Electrode System

In order to produce self-healing (failure safe), high current carrying capacitors, Sigma designed an oil printing system to produce segmented ectrode capacitor film

Machine design

Film tension control is critical for handling thin film PVDF film, which has a tendency to wrinkle and distort during machine runs. Several devices and mechanisms were introduced in order to have successful runs.

In-line Control of Electrode resistivity

The capacitor electrode is a critical component in capacitor design. Sigma designed, built and commercialized the first is the first inline optical densitometer to control the electrode resistivity in-situ.

Results

Sigma produced the highest energy density ever recorded in both PET and PVDF film capacitors, 2.56 and 6.89 J/cc, respectively.

Sigma is very excited about these results. A commercialization plan is being draft to market this new technology. The PI and Sigma are very grateful for this opportunity and thanks DTRA for its support.

SECTION 1
PROCESS DEVELOPMENT

1.1 GENERAL OVERVIEW OF THE NEW SYSTEM

Sigma Technologies has deployed over the past year an extensive effort to upgrade the NRC vacuum chamber in order to handle wider and thinner films. The new NRC Vacuum Chamber is depicted in Figure 1 and pictured in Figure 2. Major features of the new chamber include:

-48" drum for handling wide films for pilot production
-UV curing system for processing a wide range of monomer formulation
-Magnetron Sputtering for the deposition of a wide range of inorganic materials
-Use of oil heating for uniform temperature distribution
-New electron gun design
-New evaporator and nozzle design
-New rollers and drives for handling thin films
-Inline densitometer
-Control Software (Touch Screen)

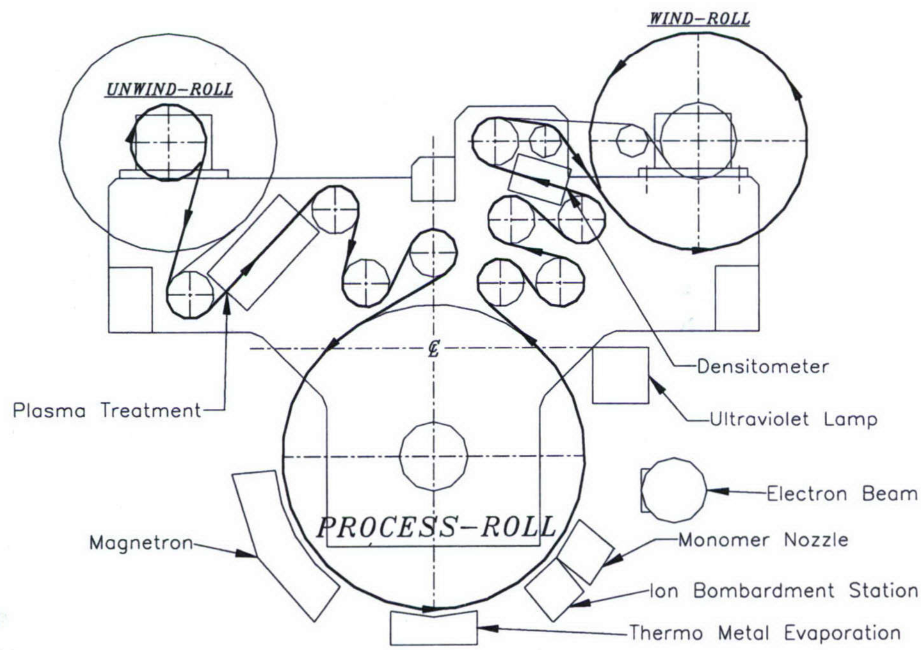

Figure 1. Schematic Drawing of the newly designed NRC vacuum chamber

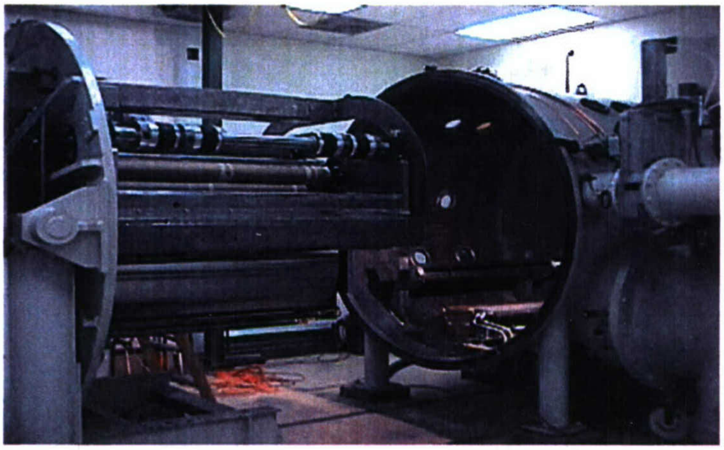

Figure 2. Picture of the new NRC Vacuum Chamber

1.2 NRC DRIVE SYSTEM

The NRC web system is composed of four drive elements, which are functionally broken into for web handling purposes. The driven elements, that being, the drum, the unwind roll, the rewind roll, and the tensioning helper, each employ an AC brushless servomotor and are shown in the attached schematic along with the positions of the three sets of which are responsible for

System control is provided by an Ormec Orion III series Motion Controller module. This device is responsible for , and overall allocation of system resources under the direction of a user implemented program. A is utilized to command and , as well as provide for the input of the necessary run parameters such as roll and cores sizes.

The basic principle behind this system calls for a servo response based on tensioning requirements. That is to say, the system calls for a servo drive response based on an algorithm that takes into account both the commanded and currently read tensions in each zone. In this fashion, control of the web is accomplished by closing the servo loops (that is their position and motion parameters) around a . Actual control depends on several nested loops and varies with the mode of operation chosen (i.e. velocity control or position control). In both cases a velocity and gearing loop are present, while in the case of position mode a positioning loop is substituted for a the tensioning loop term used in velocity mode.

Changes/Modifications:

• Various web paths, and load cell positions have been explored in order to optimize web tensioning and control. The final path is as shown in Fig. 1.

• The web was previously utilized in velocity mode. This was not the desired mode of operation, but mechanical problems with the drive system, in the form of a gearbox with poor backlash ratings, necessitated the use of this weaker control mode. This problem is being rectified via the installation of a better gearbox. The web is now currently being tuned to operate in position mode, which should improve its thin film handling characteristics.

Due to film wrinkling, bowed rollers were replaced by spreader rollers. Also, nip roller were introduced to prevent film slippage across the drum (Figure 3)

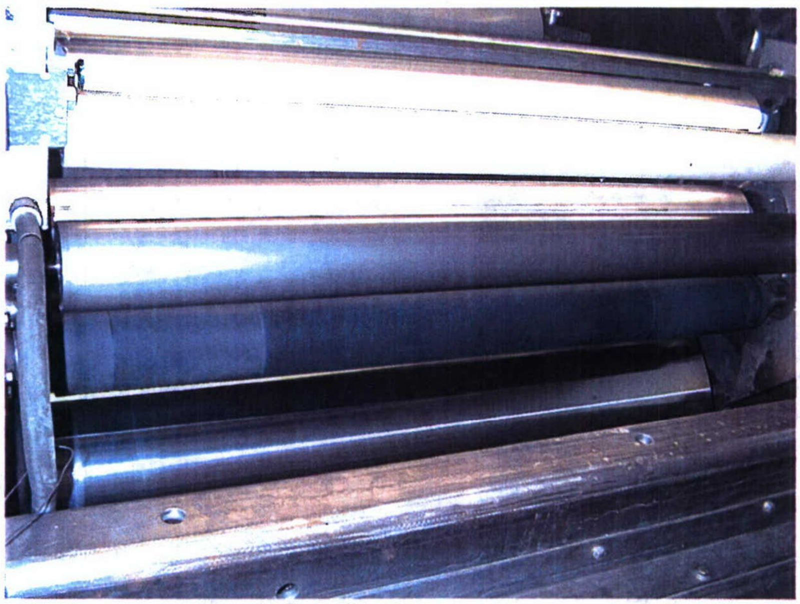

Figure 3. Rollers for thin film tensioning

1.3 MONOMER DEPOSITION SYSTEM

This system is composed of
-a degassing and pumping system,
-an oil tank,
-an evaporator, and a nozzle

The new monomer evaporation system calls for operation up to 450 °F to provide us with the ability to process high temperature polymers. The monomer syringe pump (Esco model D500) is based on positive displacement mechanisms. This pump is able to handle high viscosity monomers with good flow control. We also experimented with a parastolic (squeeze) pump (Welsh) with less success.

The electric band heater around the evaporator were replaced by an oil heater tank (shown in Figure 4) for more temperature uniformity.

The new monomer evaporator, as well as all the related accessories, were designed for handling several types of monomers with different properties that include viscosity, stochiometry, and flashing temperature. The monomer is introduced in the evaporator through Bosch type injectors. The monomer nozzle was redesigned to include variable flow rates . Strip style electrical nozzle heaters (Tempco, 600W) were used instead of band heaters .Mass flow controllers (MKS 1000) are used to control the monomer flow. Several experiments were carried out in order to optimize to whole process (flow rate, viscosity, temperature). Versions of evaporator, nozzle, and assembly design are shown shown in Figure 5 and pictured in Figures 6 and 7. also to handle high temperature monomer

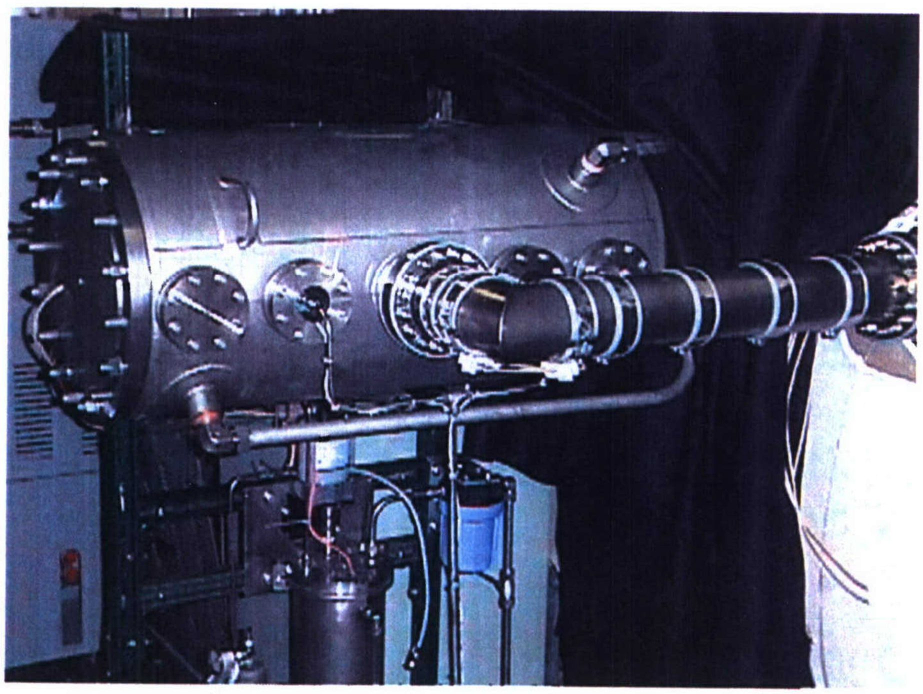

Figure 4. Oil Tank for Monomer Evaporator Heating

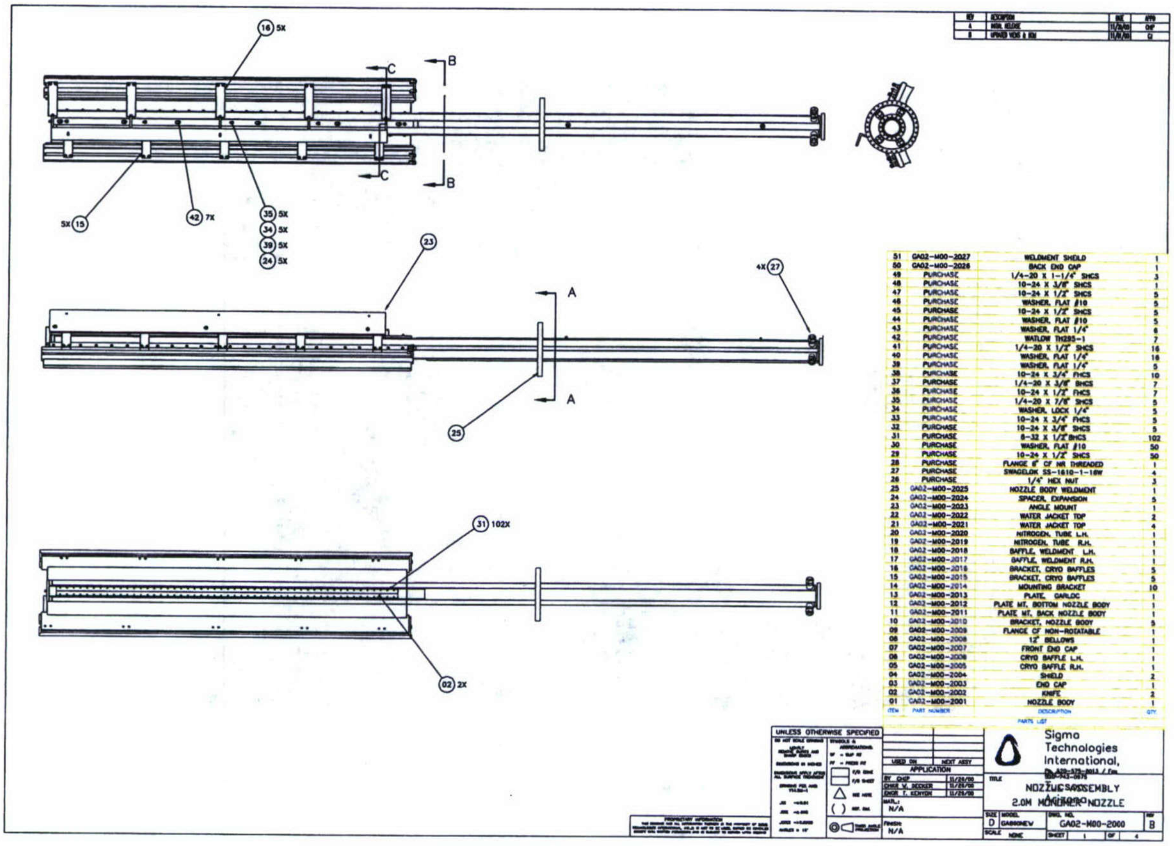

Figure 5. Evaporator and Nozzle Design

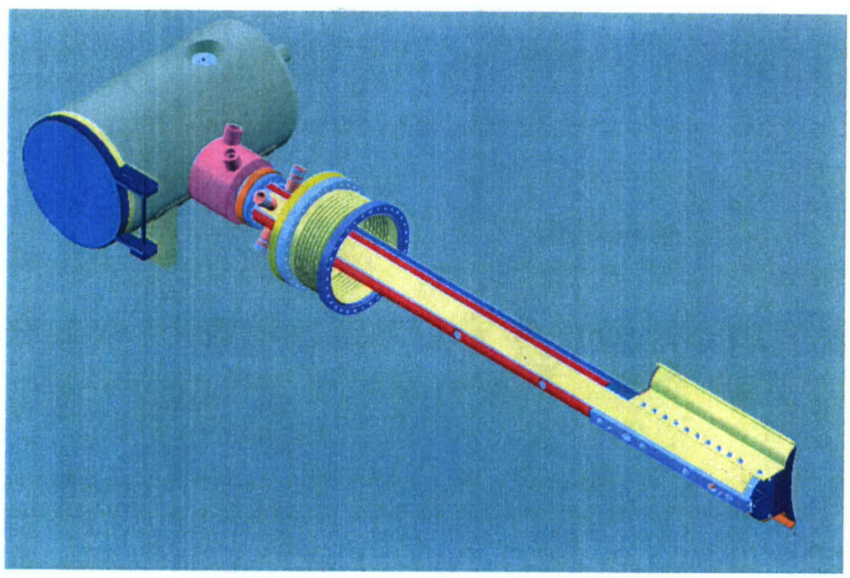

Figure 6. 3-D view of Tank, evaporator and monomer nozzle.

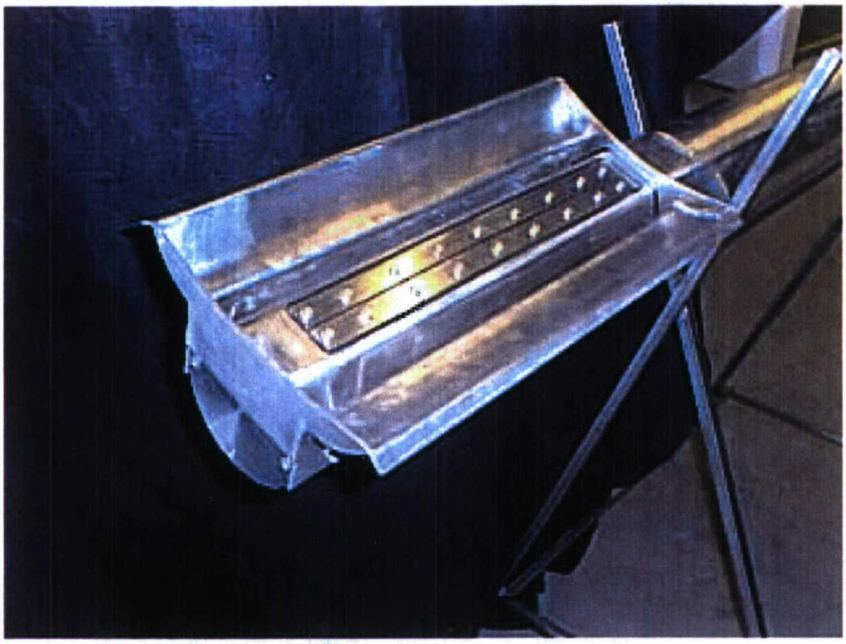

Figure 7. Picture of a monomer nozzle

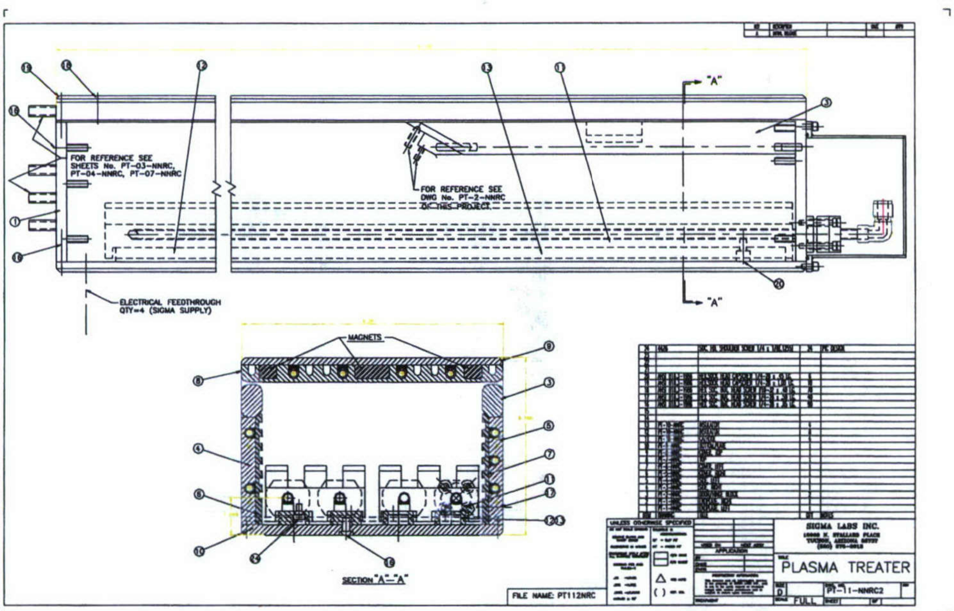

Figure 8. Plasma Treater Design

1.4 PLASMA SOURCE

The design of the new plasma gun include a dual hollow cathode and a magnetic focusing system for selective plasma treatment. An example of Plasma gun design is shown in Figure 8. A picture of plasma source is shown in Figure 9..

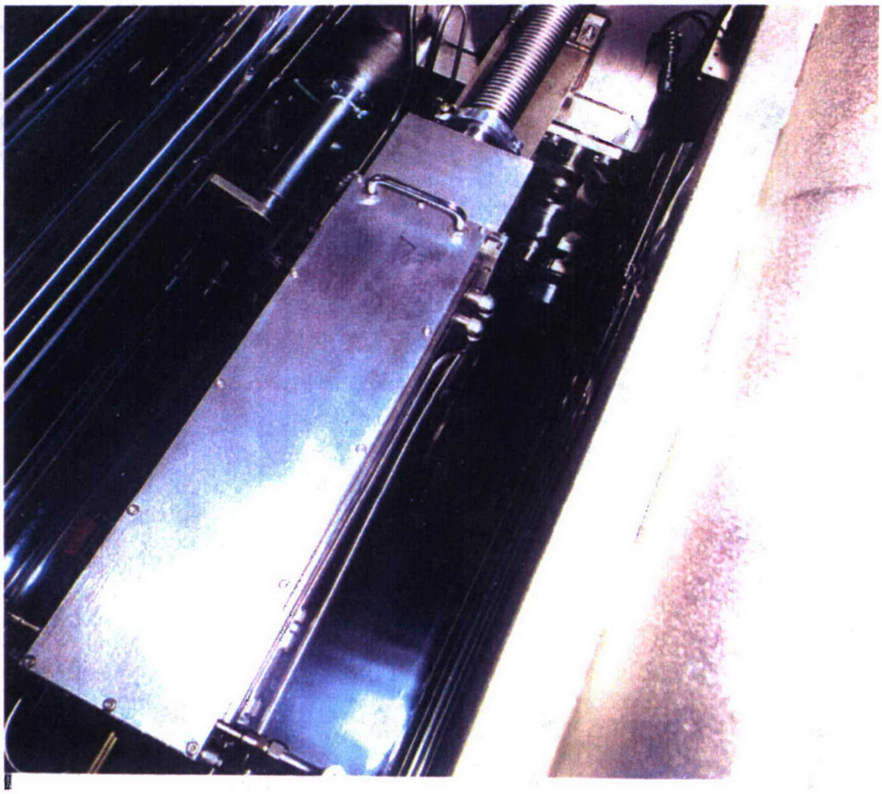

Figure 9. Picture of the Plasma Treater

1.5 ELECTRON GUN

In the new electron gun design (see Fig. 10) special attention was given to the dimension of the groove, the shape and the width of the slit, and the reactive gas manifold. Several machine runs were carried out in order to optimize the process (gas pressure, voltage, width of the slit, distance between the gun and the film) . A picture of the electron gun is shown in Figure 11. A Spellman Model SR6 supplies the control high voltage to the electron beam.

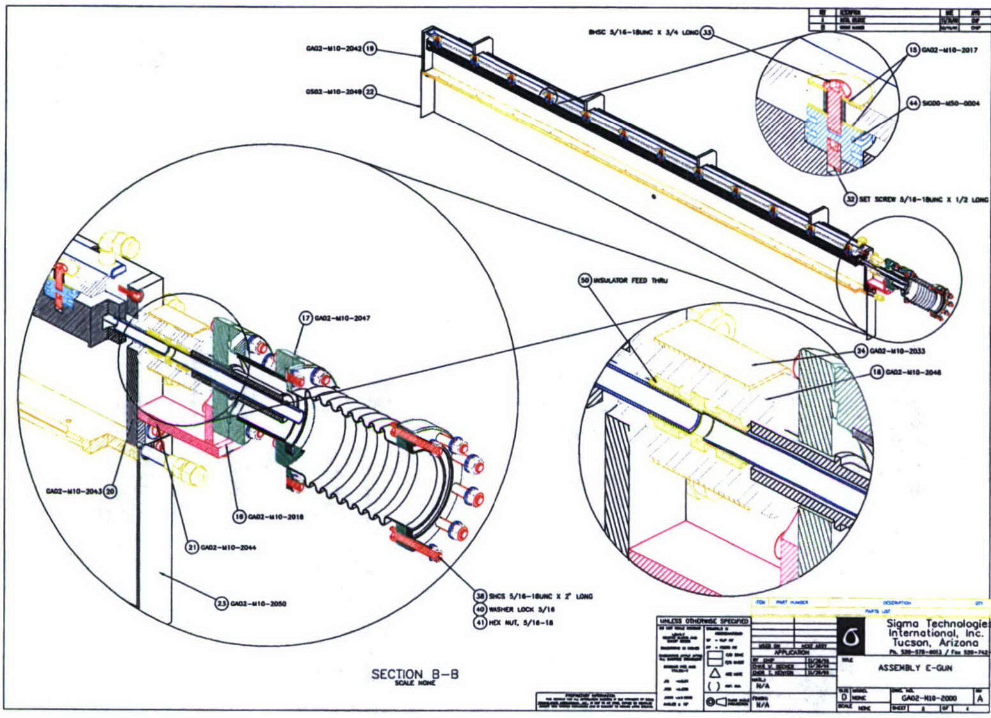

Figure 10. Electron Gun Design

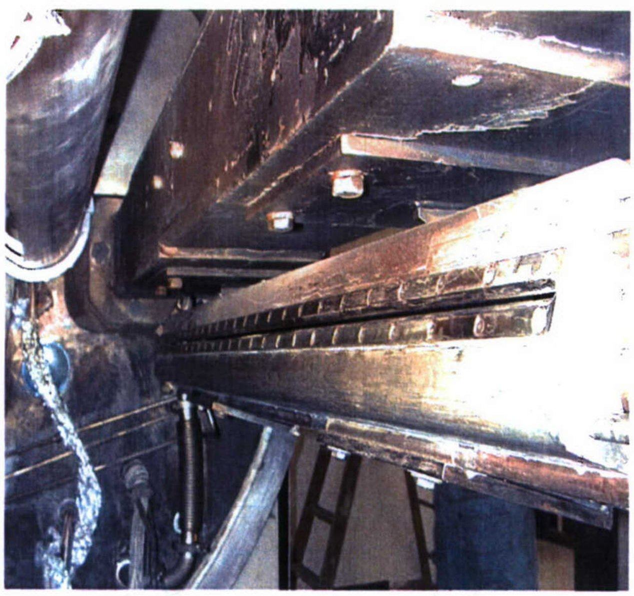

Figure 11. Picture of the electron gun as installed in the NRC

1.6 ULTRAVIOLET (UV) LIGHT SOURCE

For a certain type of polymer or for thick coatings, it is sometimes necessary to use UV light instead of electrons for proper curing. For this purpose, Sigma has incorporated a UV light source in the NRC. (see Figures 12 and 13 for the schematics and the picture.)

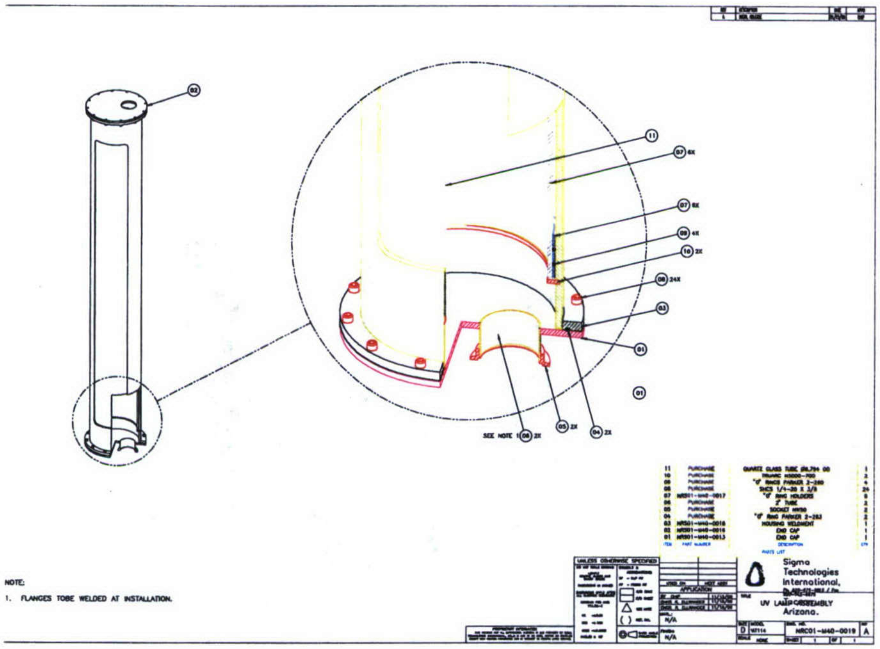

Figure 12. UV Source Design.

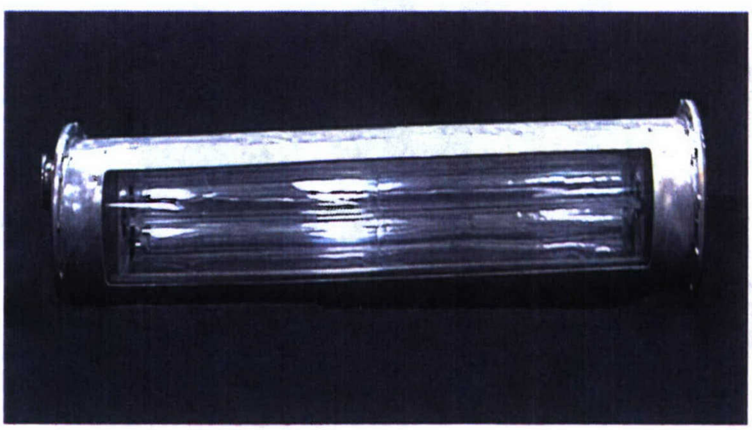

Figure 13. Picture of the UV Source.

1.7 SOFTWARE CONTROLS

PLC software was developed to control the whole process. A picture of the Sigma TouchScreen is shown in Figure 14.

Figure 14. Touch Screen Controls of the NRC

SECTION 2
INLINE OPTICAL DENSITY SCANNER

2.1 BACKGROUND

The electrical layout for the functional prototype of the Inline Optical Density Scanner is as shown in the previously submitted schematic. As a basic reminder to the reader, this circuit operates by placing a target between a series of light sources and a like number of TSL230B Light-to-Frequency sensors (see Figure 15). The output of each of these sensors is a frequency, which is linearly proportional to the intensity of the received light. Sensor sensitivity is accomplished via the selection of lines S0 and S1. These lines provide access to an internal electric iris while a second pair of lines (S2 and S3) allow for the scaling of the frequency output through an internal divide-by circuit. The output of each sensor is buffered through a 74BCT541A, and then transmitted to a nearby control board via a terminated flat ribbon cable utilizing an alternating ground arrangement. When the frequency signals reach the control board, they are buffered again (74ALS245A) and then selected on an individually basis through a 16-to-1 multiplexer. Multiplexer control, sensor selectivity, and sensor output scaling functions are each regulated through the control board's 80C32 microcontroller. Once an individual channel has been selected, the output frequency in question is directed to the microcontroller's timer 2 (T2) port, which has been configured in an external event counter mode. The integration period for timer 2 measurements is based on the predetermined overflow rate of a second internal timer, T0. Upon collection, the value captured in T2 is divided into a calibration count, which was obtained by referencing a full light or Optical Density zero condition. The log of the above quotient is then obtained via a lookup table. The resulting Optical Density figure is then passed to the serial transmission routine for transmission to a remote display while the next sensor is being processed. As seen in the earlier schematics additional circuitry employed consists of an EPROM for program memory and NV-SRAM for variable and serial buffer storage.

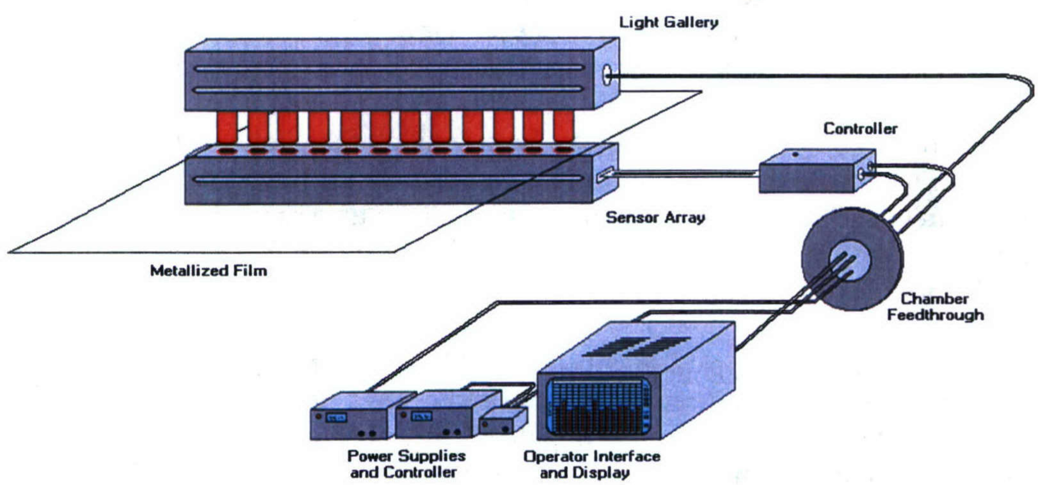

Figure 15. Inline Optical Densitometer System Overview

At present the collected Optical Density data is transmitted to a standard PC, where a Visual Basic program handles data storage and display. Concurrently, coating thickness, and ohms/square are calculated from this optical density data and are likewise stored and displayed on the host PC. Sensor control is also conducted through the host PC via an onscreen menu with the actual commands being transmitted back to the sensor through the intervening serial connection.

2.2 PROTOTYPE DEVELOPMENT

T

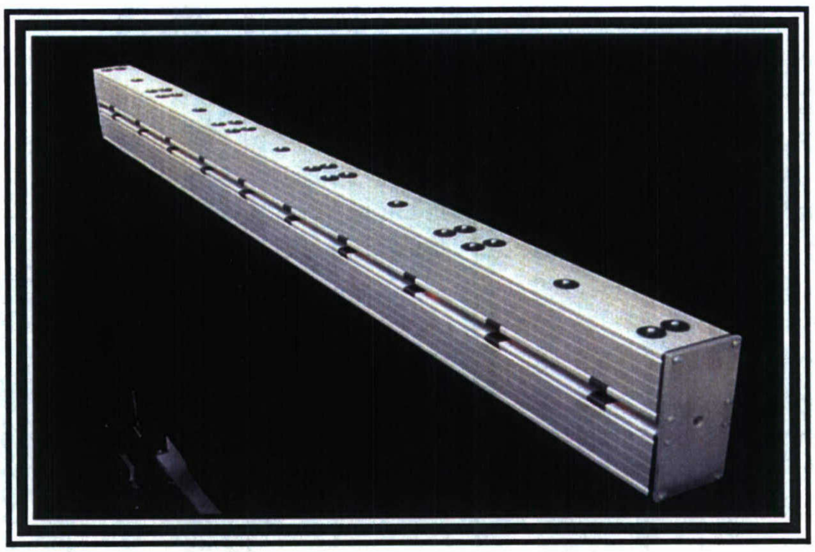

Figure 16. Sigma Inline Optical Densitometer

The prototype, as shown in Figure 16, incorporated 10 sensors spanning a 48" web path (package width is 1.5" and package depth, which includes the sensor bar, light bar, and the intervening film gap is 6.5"). The number of sensors, their spacing, and the distance spanned by the resulting sensor array is, for the most part, variable. Higher or lesser sensor densities could easily be incorporated with only minor circuitry and software changes. The selection of the light source proved more difficult. An earlier attempt to use a florescent tube was abandoned when, under vacuum, a noticeable output frequency drift was observed, even when the tube ripple frequency was rejected by integrating over one period. A row of incandescent bulbs were employed next, but these devices proved unsatisfactory.

Under bench test conditions the apparatus appeared stable (see graph 1), but under vacuum conditions the poor heat conduction resulted in increased heating of the bulb filament, which in turn, led to a "self sputtering" of the filament onto the bulb's glass envelope. This action resulted in a continual decrease in the amount of light emitted by the bulb, which of course, led to a frequency drift interpretation by the sensor array (see graph 2). Even if the "self sputtering" behavior had not

been encountered it was concluded that a filament based light source was unsuitable given the heating fluctuations within the filament.

The problem was resolved by using a row of Ultra-bright (13,000 mcd) 660 nm Red LED's. These devices were placed in a series configuration and were current controlled via a precision current sink. The LED's proved more than bright enough to resolve O.D.'s up to 4.0, and with the current control provisions, proved stable under vacuum. Laser diodes were considered but they are a number of problems associated with these devices. First, these devices are notoriously difficult to tune. Secondly, they require additional support circuitry which would have not only increased system costs, but would have increased the number of feedthrough lines required as well. In addition there are reflection problems, and most importantly, heating problems which can manifest themselves in the form of mode hopping. Short of water-cooling each diode, this made these devices a poor choice given the heat dissipation problems encountered in a vacuum environment. Of course there would have been some benefits to using a laser diode arrangement, but LED's were eventually chosen for design simplicity and cost reduction.

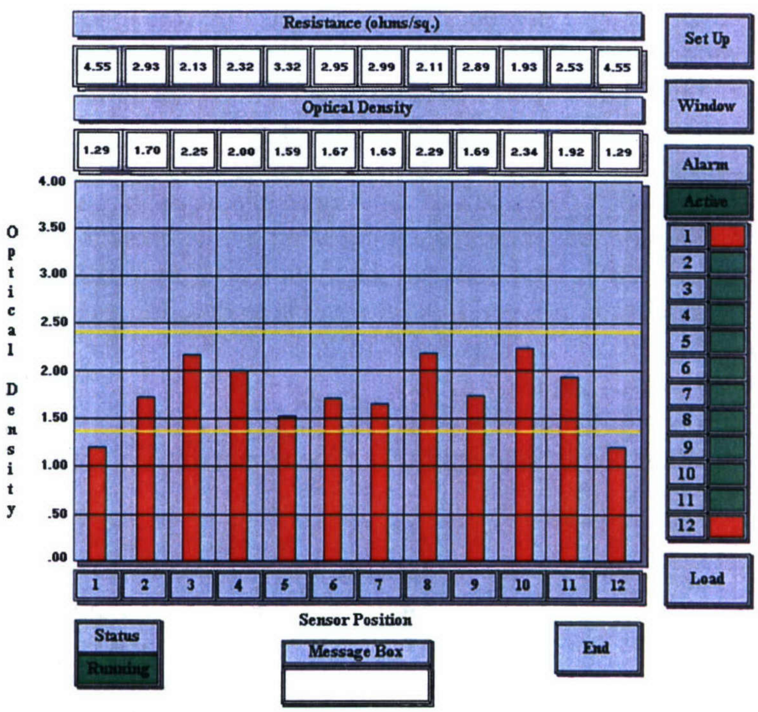

Figure 17. Operator PC Interface Screen

Figure 17 shows a representation of the operator interface screen. The current display allows for the selection of an Optical Density alarm window, the ability to turn off a specific sensor displays, various status indicators, and the display and saving of Optical Density, and Resistance/Thickness data (for Aluminum). All information and/or commands are transmitted between the control circuit and the PC via their respective serial ports at a 19,200 baud rate.

2.3 TESTING/OPERATION

A static test, under vacuum, was then conducted using a number of metalized film fragments of known optical density as targets. The results of this test, as seen in graph 3, demonstrated sensor stability. Minor variations in the known Optical Density on the order of a several one-hundredths were observed. Although these variations were within the tolerances of the Light-to-Frequency converter chips, it is more likely that the variations were a result of an extra count in the measurement approach taken.

The fact that timer 2 (the measurement counter) and the reference timer (timer 0) are not synchronized leads to an "aperture jitter" effect, which results in unintentional count variations. For lower Optical Densities this effect is not pronounced because the measured frequency is large when compared to the error. For higher optical densities however, this effect can result in problems, given that error begins to take on a larger percentage of the measured frequency. The problem can, and will be resolved by synchronizing the two counters in such a fashion that the first count of timer 2 will start the reference timer. Under these circumstances the reference timer will always begin under the same conditions.

Once the stability test was concluded a pair of aluminum evaporation metallizing runs were conducted . The verification of sensor data is complicated by the present inability to recreate the point-wise correspondence that existed between the metalized film position and the sensor reading. That is to say, once the process is stopped it is impossible to determine exactly where on the rewind roll that the sensor reading was made. This could be corrected for by accessing the web system's run counter and then saving this value along side the stored sensor data. Although the lack of cardinality between film position and sensor data is a problem for basic testing, it does not pose a problem in production, where the typical goal would be to run the entire film at a given optical density.

A general verification of the data taken in graph 4 was conducted by testing points on the produced metalized film with a bench top COSAR Transmission Densitometer. In general terms the COSAR readings supported the Inline sensor data. The COSAR showed a wide variance in film optical density over very short distances, a fact supported by the Inline sensor data. This fact was also confirmed visually by placing portions of the metallized film on a light table. Even so, the data collected in this test was in accordance with that measured by the COSAR densitometer..

In general the metalization run data is further complication by the limits of the actual metallization process itself. That is to say, the evaporation process itself is not precise. Boat histories, wire feed setups, wire feed rates, and boat resistance's can demonstrate a large variance from station to station. This fact can make data validation even more difficult.

The adjustments made by the chamber operator during the sputtering process can be seen in these graphs. Graphs 12 and 13 require an additional explanation. The 10,000 element lookup array in program memory is sufficient to characterize Optical Densities from 0 to 4. However, because of the rapid rise of the logarithm function from 0 to 1 the coverage of these optical density values in the lookup array is limited. That is to say, for lower OD values, from approximately 0 to 1, there are only a handful of elements in the array, and as such, large gaps exist between OD values in this range. To solve this problem a 100,000 element array needs to be used, unfortunately this will exceed the 64k program space of the current model. (However, the next board revision, discussed below, possess more than enough memory space to solve this problem.)

A summary of the current and future/optional scanner features is shown below:

2.4 CURRENT INLINE SENSOR FEATURES

- Measurement of Optical Densities from 0.00 to 4.00
- Selectable sensor sensitivity
- Self Calibrating
- Serial interface; reducing the number of wires required, allowing for variable hosts, and providing for increased noise immunity
- Real time display of Optical Density, and real time calculation and display of metallized film resistance, (ohms/sq.) and thickness, based on corresponding Optical Density data
- Internal control circuitry can be remotely located from the actual sensor array (up to 10 feet) allowing for mounting flexibility and space savings
- Sensing outputs and equivalent measurements are frequency based, providing for increased noise immunity and digital versatility
- Flexible. Software upgrades allow for customization with minimal
- Flexibility in sensing array dimensions and number of elements employed

2.5 OPTIONAL/FUTURE FEATURES

- Serially programmable in circuit configuration allowing for variable user defined applications and for in circuit uploading of selected lookup tables, user directives, and selected integration times
- Selectable user defined Optical Density window and sensor alarm when outside of defined range
- Selectable measurement techniques to tailor sensor speed
- Individual sensor selection and corresponding individual run history graphs
- Interface to existing web counter/web system to correlate Optical Density with actual position data
- Increased data transmission rates

2.6 IMPROVEMENTS/DEVELOPMENT DIRECTION

An improved version of the Inline system control board, which is to be built shortly, is shown in the attached diagram. This new board is centered about a more powerful 80C390 controller and will include the following features/corrective measures:

1. Increased program memory space (1 MB) and increased program data space (1 MB). This will allow for a greater number of embedded routines to be employed such as improved/selectable lookup tables, and program branching to incorporate different measurement modes.
2. Selection between frequency measurement for low O.D. (≥ 2.75) and period measurement for higher O.D.s (< 2.75) either automatically in software or by user command. The aperture jitter problem is also solved through the same mechanism. Both of the above changes are accomplished via the use of an inverter and one of the micro's interrupts. The frequency waveform to be measured is inverted and fed to interrupt 0, which is set for a falling edge interrupt. After starting the internal timer on the falling edge of the waveform, this interrupt is masked until the internal timer (T0) interrupts and completes the measurement cycle. Under these conditions frequency measurement of each waveform begins at the same point, that being, the first falling edge encountered, which should alleviate the aperture jitter problem. A period measurement scheme for higher O.D.s works along similar lines, with the exception that the internal interrupt is not masked after the start of the internal counter. Instead the interrupt is reset, and upon the next falling edge, this interrupt stops the counter. This period measurement scheme should provide better resolution for higher O.D.s.
3. An integral watchdog timer. This timer is important should the system "hang up." If the system stops the watchdog timer will time out and reboot the system. Upon reboot a calibration flag is checked. If the system has already been calibrated, that is, should the system reboot during a metallization run, this calibration flag will tell the system to use the calibrations values previously stored in the Non-Volatile (NV) SRAM. If the calibration flag is not set then the system will start the calibration routine. This system health monitoring occurs behind the scenes on the order of mSec, and thus, requires no action on the part of the operator.
4. An increased serial data rate.

5. Provisions for strobed light gallery operation and provisions for auto ranging light levels.

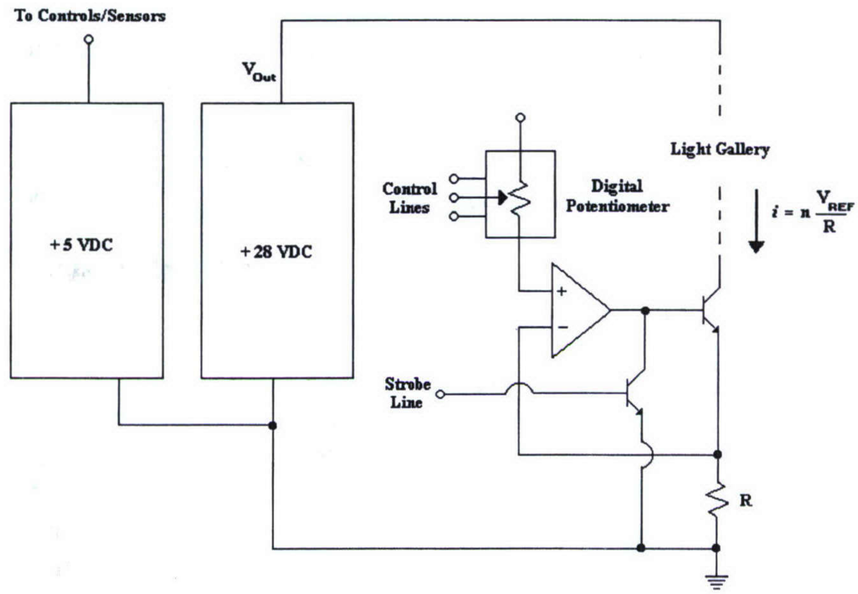

Figure 18. Light Gallery Control

(These items are explained later in the report.)

6. Improved frequency measurement range due to the inherently higher speed of the 80C390.
7. The 80C390 also has a pair of onboard full-function CAN 2.0B controllers. At the moment there is no call to place the instrument on a Controlled Area Network however, such a possibility has been reserved within the new circuitry.

It would also be desirable to provide more flexible control of the light gallery. Figure 18 shows a set of possibilities in this regard.

The first possibility would be to strobe the light gallery at a fixed frequency. The Ultra-bright LEDs are capable of very high output light levels under pulsed conditions. However, parasitic circuit elements, duty cycle, edge chirping, sensor response, pulse repeatability, and the event capture timing will all have to be characterized before such a mode can be employed. At the moment provisions for this mode of operation will be incorporated into the Rev. A board.

A second possibility would be to incorporate provisions to control the current through the gallery via a digitally controlled potentiometer. Under such an arrangement, as shown in Figure 18, the control board would have the ability to auto-range the light gallery output as needed. The idea behind this would be for the controller to step through a series of light levels by indexing the digital potentiometer. This index point would be saved as would the frequency or period calibration point

at this given light level. During operation then, the controller would select the light level required based on the observed optical density. Such an arrangement should optimize the light gallery output, which will increase light gallery life and prevent the saturation of the light sensors.

In addition to the above elements there also exists other control possibilities, should future data point to the reliability and accuracy of the Inline sensor. The most intriguing of these is closing the metallization process loop by feeding the sensor data back either to a central processing unit or via a number of DAC's to the boats' control circuitry. Such an arrangement, if feasible, would provide for efficient process control with minimal intervention on the part of the chamber operator.

2.7 NEWEST DEVELOPMENT OF HIGH DENSITY OPTICAL SCANNER FOR CAPACITIVE WINDING OPERATIONS

The schematics for the prototype of a second Optical Density scanner, for use in monitoring Optical Density during Capacitive winding operations, are shown in Figure 19 . The basic principle behind this system is similar to that of a common scanner. The transmitted light through the metallized film in question is imaged down onto a CMOS linear array. This light level information is captured, and transmitted to a level shifter/gain stage (PGA205) before being passed on to an Analog-to-Digital converter (AD976A). The digital output from this 16 bit converter is then consumed by the 80C390 microcontroller where the information is turned into an Optical Density value and then transmitted to a remote PC/display for operator use. The remaining chips provide core functions such as program and data memory. A linear CMOS array was chosen for several reasons. First, the array was easily capable of 14 bits and should actually output closer to 15.5 true bits under optimum circumstances. Secondly, unlike a CCD, the CMOS arrays require no cooling, which greatly simplified the overall circuit design. Lastly, none of the ancillary chips associated with CCD control and timing are required with the CMOS imagers.

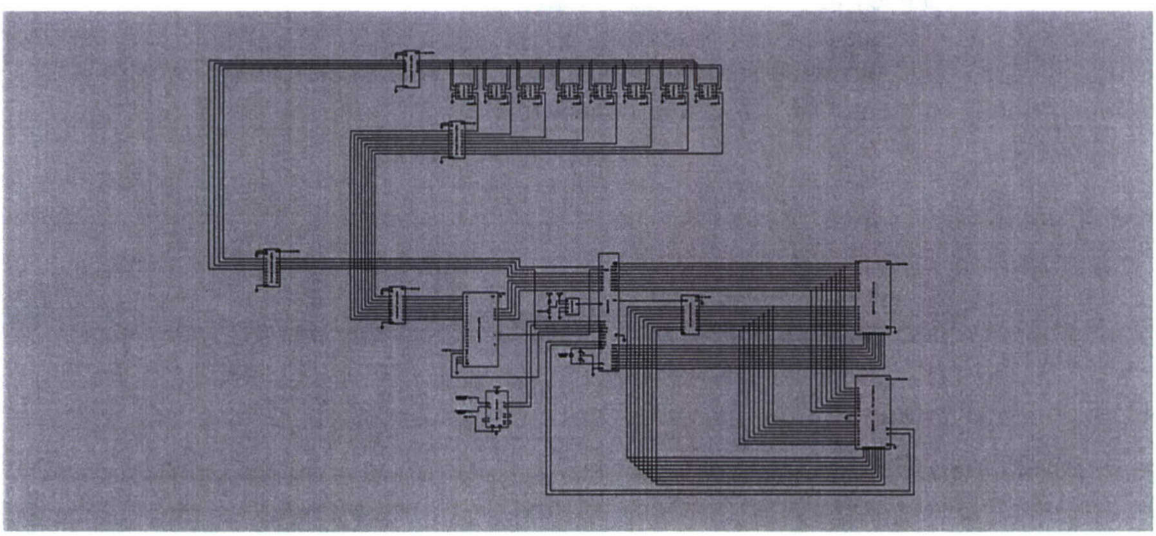

Figure 19. Schematic drawing for the prototype inline scanner for capacitor windings

2.8 CODE

The initial C code for controlling the OD monitor is the following:

```
/***********************************************************************/
/***               Optical Density Scanner Program 2                ***/
/
/***                                                                ***/
/***  This version employs a more precise lookup table which is     ***/
/***          geared for measuring O.D.s from 0 to 1.0              ***/
/***********************************************************************/
#include <AM80C52.h>
#include <stdlib.h>
#include <stdio.h>

/************** optical density program definitions *********************/
#define uchar unsigned char
#define uint unsigned int
#define ulong unsigned long
#define ushort unsigned short
bit data data_ready, start_flag,end_flag;       /* decision flags */
bit data cal_done;
bit data t_empty, t_done;                 /* serial decision flags */
uchar n,a,b;                              /* indexing variable */
uchar xdata rbuf[8];                      /* ser rec & trans buffers */
uchar xdata ascii_conv[6];                /* acsii conversion array */
ulong xdata freq_cal_data[12];            /* calibration data array */
ushort xdata freq_data[12];               /* Current freq data array */
ulong xdata freq_od[12];                  /* O.D. output array */
ushort data i;                            /* ratio index int. */
ushort code lg2[];                        /* log10 lookup table */
/*ushort code corr[];*/                   /* calibration table if needed */
/***********************************************************************/
/*                    data transmission function                       */
/***********************************************************************/
void data_tran (void){
    uchar xdata data_lo, data_hi, data_mid,d,temp;       /* var and ptr int. */
    d=0;
    EA=0;                                       /* disable interrupts */
        data_hi=freq_od[n]/100;                 /* 10ths place */
        temp=freq_od[n]%100;
        data_mid=temp/10;                 /* 100ths place */
        data_lo=temp%10;                  /* 1000ths place */
        ascii_conv[d]=0x0c;                     /* start marker */
        ascii_conv[d+1]=0x2e;
        ascii_conv[d+2]=data_hi+48;             /* save 10ths place add 48 to
make ascii 0-9 */
        ascii_conv[d+3]=data_mid+48;            /* save 100ths place */
        ascii_conv[d+4]=data_lo+48;       /* save 1000ths place */
        ascii_conv[d+5]=0x0d;                   /* end marker */
    t_empty=0;                                  /* sbuffer not empty */
    EA=1;                                       /* enable interrupts */
    SBUF=n+48;                                  /* send-start data stream-sensor
number */

}
```

```
/*************************************************************************/
/*                serial interrupt service routine                        */
/*************************************************************************/

void serint(void) interrupt 4 using 1 {
    static uchar a,b;
    if (RI==1){
        rbuf[a]=SBUF;                   /* rec char save to rec buffer */
           if (rbuf[a]==0x53){
                start_flag=1;           /* 'S' calibrate & start */
           }
           if (rbuf[a]==0x45){
                end_flag=1;             /* 'E' end run */
           }
    }
        a=++a && 0xf;                   /* index buf & check rollover (not
needed) */
        RI=0;                           /* clear interrupt */
    if (TI==1 && !t_empty){
        SBUF= ascii_conv[b];            /* trans complete, load next item */
        b++;
        TI=0;                           /* clear interrupt flag */
            if (b==6){
                t_empty=1;              /* tbuffer empty flag or rollover */
                b=0;                    /* reset tbuffer index */
            }
    } else {                            /* at end of tbuffer */
        TI=0;                           /* clear trans interrupt */
        t_done =1;                      /* tbuffer sent */
    }
}

/************************************************************************/
/*                      read_sensor function                            */
/************************************************************************/
void read_sensor (void) {
    uchar a=0;
    TH0=0, TL0=0;               /* clear timer 0 */
    TH2=0, TL2=0;               /* clear timer 2 */
    a=n;
    a <<= 4;                    /* shift to upper 4 bits of port 1 */
    if (cal_done==0) {
        a |= 0x07;              /* in cal routine mask off div. by 100 */
    } else {                    /* output scaling and x10 sen settings */
        a |= 0x06;              /* in data routine mask off div by 2 */
    }                           /* output scaling and x10 sen settings */
    P1=a;                       /* write to mux via port 1 */
    TR0=1;                      /* start timer 0 - freq counter */
    TR2=1;                      /* start timer 2 - internal timer */
}

/************************************************************************/
/***                 Timer 2 interrupt service routine                ***/
/************************************************************************/

void timer2() interrupt 5 using 1 {
```

```
    TR0=0;                     /* stop timer 0 - counter */
    TR2=0;                     /* stop timer 2 - internal timer */

    TF2=0;                     /* clear interrupt flag */
    data_ready=1;              /* set the data ready flag */
}

/*************************************************************************/
/***                           Main                                    ***/
/*************************************************************************/

void main (void)
{
   EA=0;                        /* Disable interrupts */
   C_T2=0;                /* T2 as internal timer */
   a=0, b=0;
   TMOD=0x25;                   /* T1 mode 2, T0 16bit counter */
   TH1=0xfd;                    /* reload, T1 used as 9600 baud rate gen. */
   TCON=0x40;                   /* start T1 */
   SCON=0x50;                   /* serial mode 1, 8-bit UART */
   EA=1,ET2=1,ES=1;             /* interrupt enables T2,and serial */
   ET1=0,EX1=0,PS=1;            /* int. pr. reg. serial high */
   ET0=0;EX0=0;                 /* set desired interrupts */
/***********************************************************************/
   while (start_flag !=1)
       ;                          /* do nothing untill set */
   P3_2=1; P1_1=1;                /* s0=0, s1=1 - x100 sensitivity */
   P1_2=1; P1_3=0;                /* s2=1, s3=1 - div. by 2 output scaling */
   P1_4=0; P1_5=0;                /* clear port 1 mux select lines */
   P1_6=0; P1_7=0;
/***************** set up cal data loop *******************************/
   for (n=0; n<12; n++)
   {
       read_sensor ();
       while (data_ready !=1)
           ;                       /* wait until timer 2 overflows */
       freq_cal_data[n]=TH0;   /*high byte */
       freq_cal_data [n] <<= 8;  /* shift into upper byte */
       freq_cal_data [n] |= TL0; /* put lower byte in */
       data_ready = 0;           /* clear data flag for next measurement */
   }
   cal_done = 1;                 /* calibration complete flag */
   n=0;                          /* reset index */
/*********************** Data collection ********************************/
   cal_done=0;                  /* reset cleared by status */
   P3_2=1, P1_1=1;                /* s0=0, s1=1 - x100 sensitivity */
   P1_2=1, P1_3=0;                /* s2=1, s3=0 - div. by 2 output scaling */
   P1_4=0, P1_5=0;                /* clear port 1 mux select lines */
   P1_6=0, P1_7=0;
/********************* set up data loop ******************************/
   while (end_flag!=1)
   {
       for (n=0; n<12; n++)
       {
           read_sensor ();
           while (data_ready != 1)
               ;                          /* wait for timer 2 to overflow */
```

```
            freq_data[n]=TH0;             /* high byte */
            freq_data [n] <<= 8;            /* shift into upper byte */
            freq_data [n] |= TL0;           /* put lower byte in */
                if (freq_data[n] == 0){
                    freq_data[n] = 1;
                }                           /* error trap freq_data value */
            i = ((100*freq_cal_data[n])/freq_data[n]);
            freq_od[n]=lg2[i];
            /*freq_od[n] = (corr[n])*(freq_od[n]);    /* O.D. calculation and
offset correction */
            /*freq_od[n]=freq_od[n]/1000;     /* correction factor is in 1000's
convert back */
            data_ready = 0;                 /* clear flag for next measurement */
            data_tran();                    /* send data */
          while(t_done != 1)
             ;                    /* wait for data to be sent */
            t_done=0;                   /* reset done flag*/
        }
    }
 /******************** end of run ***************************************/
            ascii_conv[0]=0x44;            /* load end message into buffer */
            ascii_conv[1]=0x6f;            /* and transmit */
            ascii_conv[2]=0x6e;
            ascii_conv[3]=0x65;
            ascii_conv[4]=0x0d;
            SBUF=0x0c;
            while(t_done !=1)          /* Wait for end message to be trans */
                ;
   /* Done */

}
```

Sigma was successful in commercializing the OD monitor to several Metallizing plants here and abroad. The documentation for the commercial devices are shown below.

SECTION 3
USER'S MANUAL

3.1 INTRODUCTION

The Sigma Inline Optical Densitometer is a self-contained instrument designed to monitor metallization process parameters inline. Calibration, error checking, data manipulation and data transmission are all performed within the actual device allowing the user the flexibility to employ the Densitometer in a stand alone mode or within the confines of a system loop. The Inline Optical Densitometer is designed to measure and display optical densities from 0.00 to 4.00. Coating thickness and resistivity, in ohms/square, are calculated from this optical density data and are likewise stored and displayed on the host PC. Sensor control is also conducted through the host PC via an onscreen menu with the actual commands being transmitted back to the sensor through the intervening serial connection(s). An overview of the Densitometer and its system components is shown below in Figure 20.

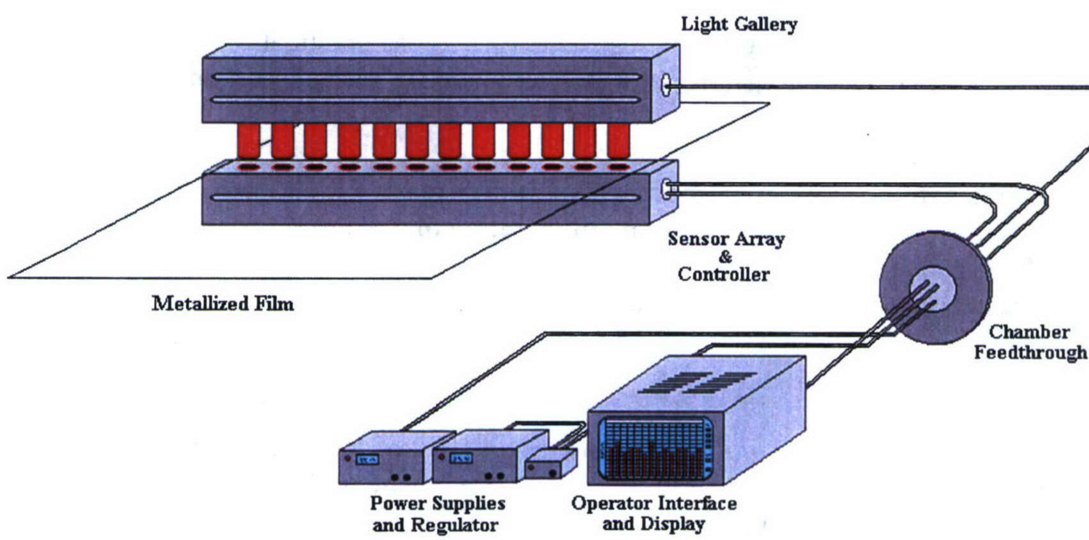

Figure 20. Sigma Optical Densitometer System

3.2 INSTALLATION

Installation of the Inline Optical Densitometer consists primarily of physically mounting the device within the users vacuum chamber and then making the appropriate signal and power interconnections.

a) Physical Mounting:

Some care should be taken in the selection of a mounting location for the Densitometer. The device should be mounted perpendicular to the web within the rewind section of the users web system in a location that minimizes exposure to metal flakes and contaminates that are often present within the metallization process. Although there is no orientation associated with the apparatus, common practice is to mount the device with the light gallery above the web and the sensing array below the web as shown in figure 1-1. Such an arrangement can simplify routine cleaning and maintenance and will minimize any stray light pollution from entering the device's sensor array.

The actual physical mounting of the device depends on the users chamber configuration, and available space. Given the variance in these conditions specific information cannot be given on the actual mounting method best employed. Whatever the bracket arrangement decided upon by the user, actual connection to the Densitometer is accomplished via the two through holes that have been placed at the center of the "H" brackets that connect the upper and lower sections of the device. Fortunately, mounting is somewhat simplified by the fact that the Densitometer itself is not a heavy apparatus and as such does not require substantial arrangements to hold it in place.

The checklist below gives a brief overview of what should be observed when considering the Densitometer's mounting location.

1. Place within rewind section of web as close to rewind roll as practical.
2. Place the device in a location that minimizes its exposure to metal flakes and process contaminates.
2. Orient apparatus perpendicular to the web.
3. Place the device in such a fashion to prevent or minimize stray light from entering the sensing array. This may require examining the location of the current chamber light if one is utilized.
4. Place the device in a location that allows for easy routine cleaning and maintenance.

b) Interconnections:

The actual signal and power interconnections are accomplished by consulting the interconnect diagrams shown in figures 21, 22, 23 and the accompanying interconnect legends. Connections from the device should be routed to the nearest electrical feedthrough, and after exiting the chamber, to the appropriate external locations (i.e. power supply cabinet or computer display). In most cases the interconnecting wiring is color-coded and this color-coding should be adhered to in order to simplify the installation process and any future maintenance issues.

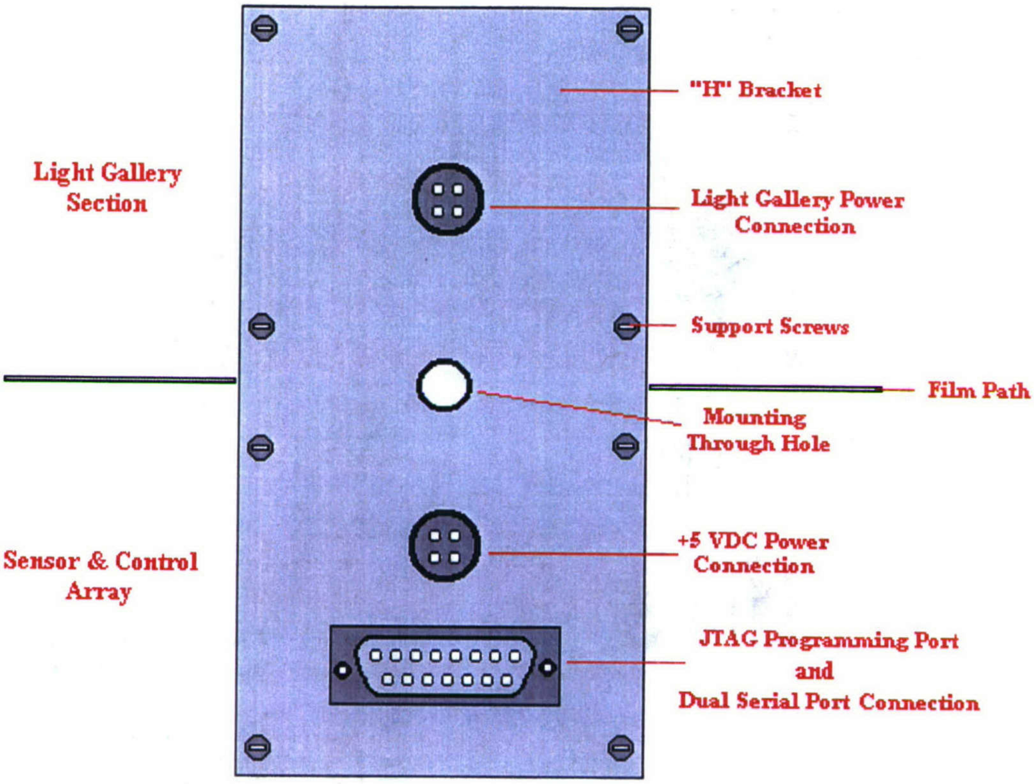

Figure 21. Densitometer Connections

Figure 21 Legend

Power Connectors:

+5 - +5 VDC power (two left hand pins in above diagram)
Gnd - system ground (two right hand pins in above diagram)
In - input to light array from regulator
Return - return from light array to regulator

15 Pin Male D Connector:

Pin 1: R1 - receive serial port 1
Pin 2: T1 - transmit serial port 1
Pin 3: G - System Ground
Pin 4: G - Ground
Pin 5: LF - Light Array Fail Signal
Pin 6: R2 - receive serial port 2

Pin 7: T2 - transmit serial port 2
Pin 8: G - System Ground
Pin 9 thru 14: JTAG - programming interface
Pin 15: NC - Not connected

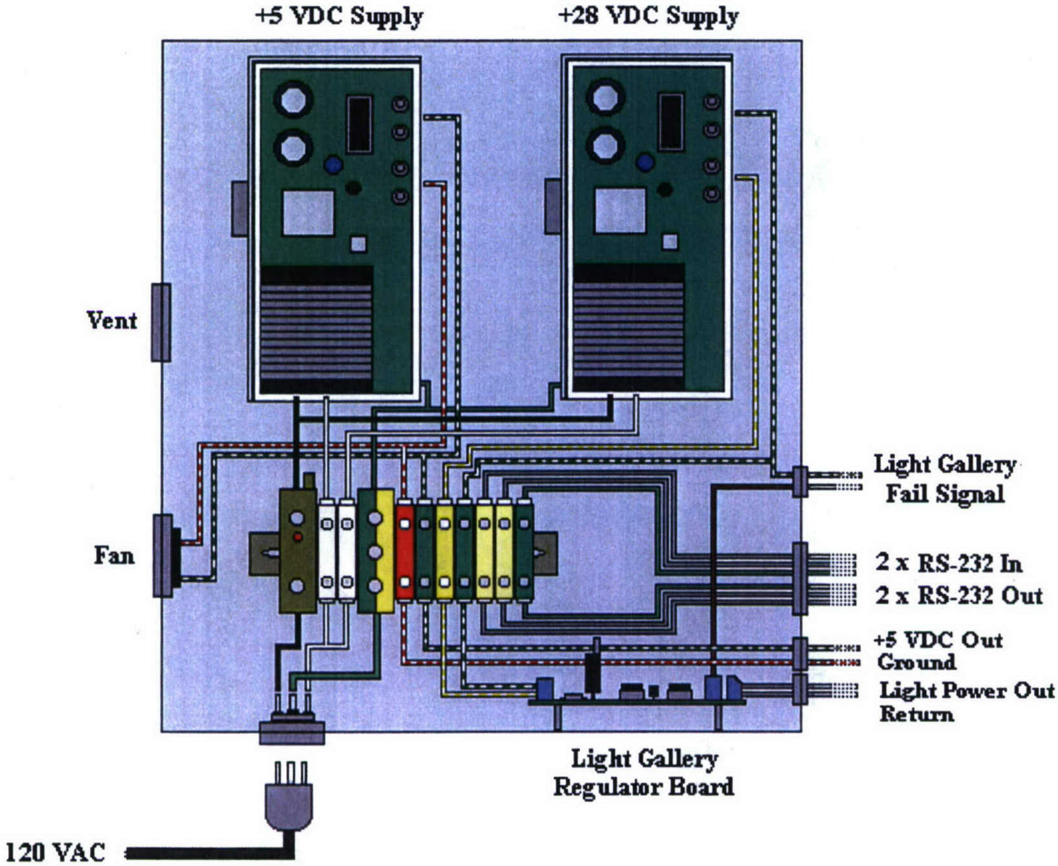

Figure 22. Power Cabinet Connections

<u>Figure 22 Legend</u>

Wire Color	**Block Color**	**Signal**
Green/White	Green	DC Ground/Common
Red/White	Red	+5 VDC
Yellow/White	Yellow	+28 VDC
Black	N/A	Regulator output
Blue	N/A	Light Fail
Black	Tan (Fuse Block)	120 VAC
White	White	Neutral
Green	Green/Yellow	Earth Ground
Black	Tan	Transmit 1 (Serial Comms)
Red	Tan	Receive 1 (Serial Comms)

Black	Tan	Transmit 2 (Serial Comms)
Red	Tan	Receive 2 (Serial Comms)

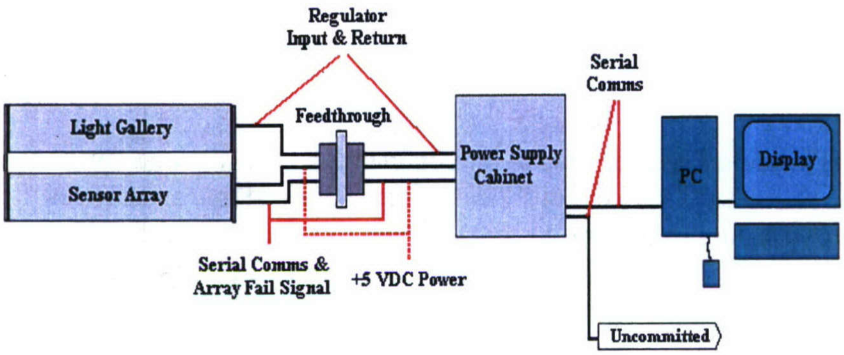

Figure 23. Interconnect Overview

Figure 23 Legend

Subsystem	Wiring Connections
Light Gallery Power	Black & Red - input to array from regulator board Green - return 1 from array to regulator board Brown - return 2 from array to regulator board
Sensor & Control Power	Red & Black - +5 VDC from power supply cabinet Green & Brown - Common from power supply cabinet
Light Gallery Fail Signal	Blue - from power supply cabinet
Serial Communications (1)	Red - (receive) to power supply cabinet Black - (transmit) to power supply cabinet Green - Common to power supply cabinet
Serial Communications (2)	Red - (receive) to power supply cabinet Black - (transmit) to power supply cabinet Green - Common to power supply cabinet
Serial Communications (1)	Red - (receive) from power supply cabinet to PC

	Black - (transmit) from power supply cabinet to PC Green - Common from power supply cabinet to PC
Serial Communications (2)	Red - (receive) from power supply cabinet to --- Black - (transmit) from power supply cabinet to --- Green - Common from power supply cabinet to ---

3.3 SYSTEM STARTUP

Once the Densitometer is mounted and the wiring interconnections are in place the system is ready for its initial startup. The following checklist outlines the procedural steps, and the resulting actions for a typical startup. Note that the initial steps (1 to 3) of the procedures are order sensitive. If problems are encountered consult the troubleshooting guide at the end of this document or by clicking on the system help button on the User Interface Program.

a) Startup:

Step 1: Turn on PC power and start program CanSlitOD by double clicking the icon.

Result: The Densitometer User Interface program will be displayed.

Step 2: Make sure that there is a clear film path between the light gallery and the sensor array and turn on Power Cabinet power.

Result: The Light Array will be illuminated and the Densitometer will begin its initial calibration and setup programs.

Step 3: Allow the light Gallery a few minutes to stabilize. Although it is not necessary, at this point it is good practice to RECALIBRATE the light array. Click the START button on the User Interface Display.

Result: Several items should be noticeable at this point. First, The START button will change to green and display the message "RUNNING." Second, the operator should see the system status box display switching between DATA, PROCESS, and OK. The actual order of these messages is not important. Thirdly, the operator should see a number of red bars across the bottom of the display. These bars will alternately change between .02 and zero for each sensor. This is done to indicate that the Densitometer is up and running even when the Optical Density present is zero, which otherwise would yield no operator feedback other than changes in the system status box. Fourth, the LIGHT ARRAY button should be green which indicates no faults in the light array circuitry.

Step 4: If desired click the SETUP button to enable the Thickness or Resistivity display.

Result: The SETUP button will change to green and the Thickness or Resistivity display will be enabled.

Step 5: At this point all additional User functions such as ALARM, HALT, RECALIBRATE etc. are enabled and may be selected as described in Section 1.5.

Result: See Section 1.5 for specific details on User Controls.

Step 6: The Densitometer is ready.

Result: N/A

b) Shutdown:

Step 1: Select END on the User Interface program.

Results: An END message will be displayed in the System Status Box and the User Interface program will no longer update. At the same time a message will be sent to the Densitometer to terminate its data collection routines.

Step 2: End the User Interface program by clicking the X box in the upper right hand corner of the display and turn power off to the Power Supply Cabinet.

Result: The system is shutdown.

3.4 THEORY OF OPERATIONS

The Sigma Inline Densitometer operates by placing a target between a series of fixed light sources and a like number of sensors as shown in Figure 20. The resulting sensor light current is then converted to a frequency output, which is linearly proportional to the intensity of the received light. The frequency output of each sensor is buffered and then transmitted to a nearby control board. When the frequency signals reach the control board, they are then selected on an individually basis via a multiplexer. Multiplexer control, sensor selectivity, and sensor output scaling functions are each regulated through embedded routines on the control board and seldom require modification. Once an individual channel has been selected the output frequency in question is compared to a calibration frequency, which was obtained by referencing a full light or Optical Density zero condition. The calibration or base frequency is obtained by entering the systems calibration routine while the device is exposed to a known optical density condition, which is typically zero (i.e. only clear film present). Although OD zero is the predominant calibration point the device may be calibrated on any OD target value. Doing so however, will yield the display of a differential OD measurement, which in some instances may prove useful. The log of previously mentioned ratio is then calculated, as shown below, to yield the dimensionless Extinction or Optical Density value.

$$\textit{Optical Density} = \log\left(\frac{T_{cal}}{T_{data}}\right)$$

where;

T_{cal} = Calibration frequency
T_{data} = Measurement frequency

The resulting Optical Density figure is then passed to the serial transmission routine for transmission to a remote display while the next sensor is being processed.

3.5 CONTROLS

With the exception of the application of device power, all device controls are accessed via the Graphical User Interface (GUI) program on the accompanying PC. In addition, run data is saved to a file of choice for further or future consumption. A graphic of the User Interface program is shown below in figure 24.

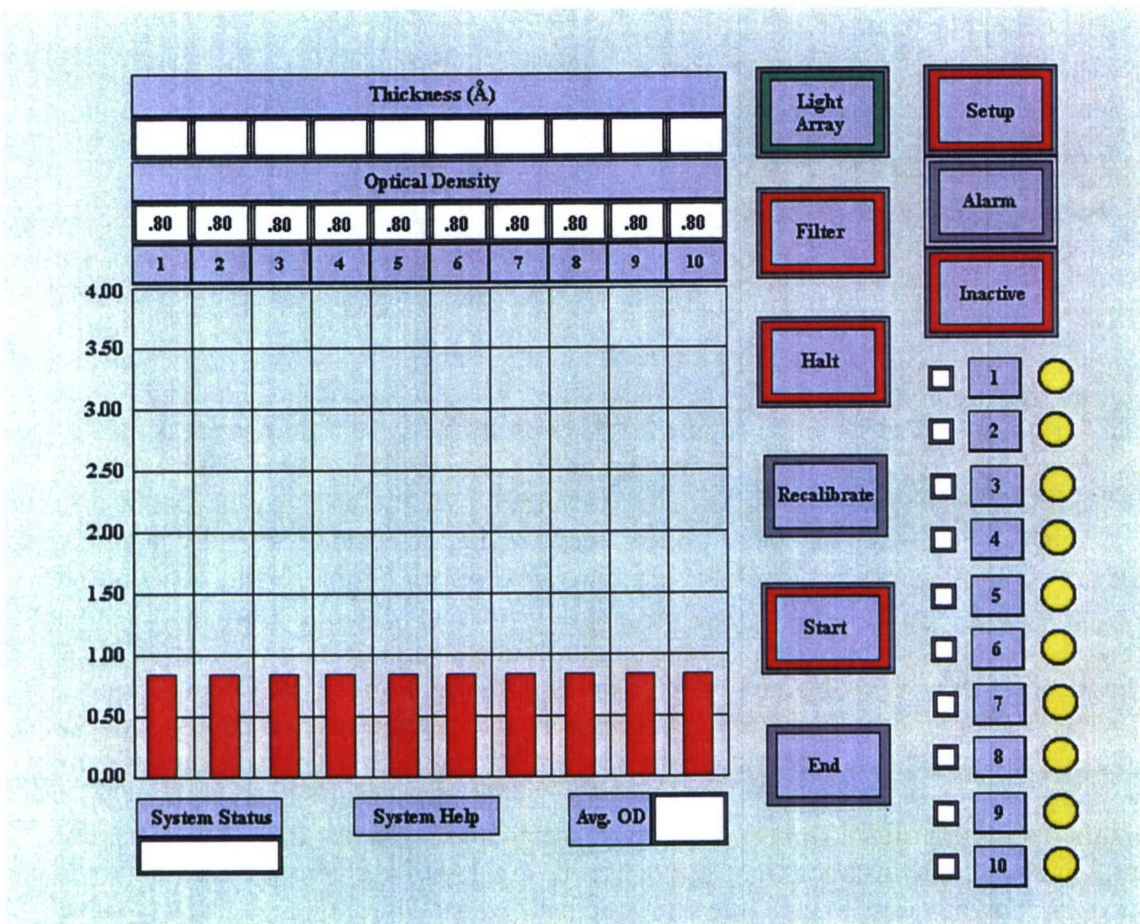

Figure 24. User Interface

3.6 CONTROL SPECIFICS

Main Display: Display of the current Optical Density value for any given sensor is accomplished via a series of red bars located in the central portion of the User screen. The numeric value of the graphical display is presented in the display box located directly above each of the bars. In a similar fashion, the equivalent Resistivity or Thickness for the given OD is shown in a series of display boxes along the top of the User screen. Toggling on the Resistivity or Thickness button bar displays the other function.

System Status: This display box is used to inform the operator of system status messages, errors, and general progress. Table 1 below summarizes the status messages encountered.

Table 1. Status Messages

Message	Status
DATA, PROCESS, OK	Normal Operations
END	End program
HALT	Program/System paused
RECAL DONE	Sensor Recalibration complete

Avg. OD: This box displays the average Optical Density across the web.

System Help: Selecting this button will cause a help menu to be displayed on the screen. This online help menu consists of three additional selections Controls, Troubleshooting, and Procedures. Selecting the desired button will display a brief help file on the subject chosen. The menu and files are closed out by selecting the X box in the upper right hand corner of each display.

Light Array: For normal operations this button should be green indicating normal light gallery operations. If a failure occurs in the light array the button will turn red and the button label will change to "FAIL." Once the problem has been cleared click on the Light Array button to reset the array status.

Filter: Activation of this button will invoke a data filter routine in which a number of samples are averaged before the display is updated. Because of this the display will update at a slower rate, but the resulting data will be smoother in nature. The Filter routine is useful for high Optical Densities (OD > 3.00) where, because of the logarithmic nature of optical density, even smaller changes in light can result in large display changes. When activated the Filter button will turn green. Selecting the button again will discontinue the filter algorithm and return operations to normal data mode.

Halt: Activation of this button will place the Densitometer in a suspended or paused mode. During this time no data will be collected or displayed. All data calibration points are preserved and normal operations can be resumed by selecting the Halt button again *followed* by clicking the Start/Running button. Green indicates Halt mode. Red indicates normal operations.

Recalibrate: Selecting this button will cause the sensor array to calibrate (recalibrate) on the current Optical Density present between the light and sensor arrays. The system will suspend operations and a RECAL DONE message will be displayed in the System Status box upon completion of the recalibration routine. To resume normal operation select the Start/Running button after the recalibration has been completed.
Note: The recalibration button should be used with some care. Upon invoking the recalibration routine the former sensor calibration points are replaced with new points. This can lead to confusing readings if it is done while a target of OD greater than zero is present within the device. Under such circumstances the resulting User display will be offset from the original OD zero base point. For instance, if the sensor is recalibrated while a target of OD 1.00 is present, the resulting display will treat OD 1.00 as zero. Any OD below 1.00 will be ignored given that Optical Density is defined as a positive number and the only values displayed will be increases in Optical Density beyond the new zero threshold of 1.00. On the other hand, recalibrating the device under the circumstances outlined above can prove useful in the form of a differential measurement regime. If the device is calibrated on an OD greater than zero the resulting display will only reflect increases in Optical Density that occur because of material additions to the base OD of the film.

Start: Activating the Start button will place the device in normal data collection mode so long as power to the device is present. Upon selection the Start button will turn green and the button label will change to "Running." The Start button is also used to resume normal operations after a Recalibration or a Halt command. (See above.)

End: This button terminates data collection and is used to implement a complete system shutdown.

Setup: Selecting this button initializes the Thickness and Resistivity arrays, which are indexed based on the current OD measurement. Setup has no effect on any other element of the OD measurement and need not be invoked if such data is not required or increased display speed is desired.

Alarm: This button is used to employ alarm checking limits and is used in conjunction with the Inactive/Active button and the alarm indicator lights located directly below it. Upon activating the Alarm button the User will be presented with a pair of dialog boxes in which the upper and lower alarm limits are set. Upon completion of this task a pair of broken blue lines, which reflect the inputted limits, will be displayed across the screen. Selecting the toggle button, Inactive/Active, will begin the alarm checking routine.

Inactive/Active: As previously described this button is used in conjunction with the alarm checking routine. When alarm checking is suspended or inactive this button will be red and will display the label "Inactive". Upon selection and activation this button will turn green and will display the label "Active."

Sensor Display & Alarm Indicators: Upon activation of the alarm checking routine the column of sensor alarm indicator lights located below the Alarm and Inactive/Active buttons will change color from yellow (inactive mode) to red or green. Any sensor with an OD value within the defined limits will have its alarm indicator light changed to green, while a sensor with an OD value outside of the

defined limits will have its alarm indicator light changed to red. Alarm checking for any given sensor can be suspended by selecting the small check box located to the left of the sensor indicator. The given sensor will then have its indicator light changed to yellow to designate suspended or disabled alarm checking. Alarm checking for all sensors can be disabled by toggling the Inactive/Active button back to Inactive. All sensor indicator lights will then return to their yellow display state. Alarm checking can be altered or performed at any time prior to or during a metallization run.

The sensor buttons located aside the alarm indicator lights also serve an additional function beyond indicating the actual sensor position. Toggling on any of these buttons will remove that sensor's bar display from the GUI. The message "off" will be displayed in that sensor's OD display box to indicate that the given sensor display has been disabled. Toggling on the button again will return that sensor's bar display and its numerical OD display back to the normal (on) state.

Saved Data: Optical Density data is automatically saved to the file ODdata located in the Sigma root directory. The time and date of the sample along with the actual sensor values are saved in a comma delimited file which can be directly imported into most spreadsheet programs. Data for several runs may be saved in this file, however the file should be occasionally moved or deleted to prevent it from becoming unwieldy. The program will automatically create a new file should the old one be removed or displaced.

Table 2 should be used as a troubleshooting table should problems occur with the startup or operations of the Sigma Inline Optical Densitometer. In some instances the operator will be referred to the Maintenance section of this manual for the corrective action or solution to the encountered problem.

Table 2. Troubleshooting Guide

Problem	Cause/Corrective Action
GUI stops functioning or displays an error message.	Restart GUI program. Note that although the GUI has stopped processing data the Densitometer is still running and transmitting data. Restarting the GUI will resume data collection and display.
Light Array Failure indicator turns red and displays the message "FAIL."	A transmitter in the gallery has failed or the regulator board has malfunctioned. (See the Maintenance section for corrective action).
The GUI display will not update and shows only "Data" in the status box.	Communications failure: Restart the GUI. If the problem does not clear check the serial output from the Densitometer by placing a scope across the appropriate terminal blocks in the power supply cabinet. If the serial communications are present the problem is in the connection lines between the power supply cabinet and the computer or with the computers serial port routines (via the computers operating system). Restart the computer and the GUI to eliminate the last possibility and check the connections between the cabinet and the computer. If the serial communications (transmit) are not present at the terminal blocks the problem is in the Densitometer's embedded routines. Restart the Densitometer by cycling power to the device. (See maintenance section for additional details.) NOTE: All calibration data will be lost once power is cycled to the Densitometer.
System fails to communicate and light gallery fails to illuminate.	Verify that power to the power supply cabinet is "on." Check power at the terminal blocks within the cabinet and at the power connectors of the light gallery and sensor array.
At high ODs the bar display bounces	Apply filter routine to smooth data. At high ODs very little light is entering the sensor. This coupled with the logarithmic nature of optical density can lead to a bouncing effect in the readings if even small OD changes are encountered.
No power to Densitometer/Light Array	Disconnect 120VAC from the power supply cabinet and check fuse in fuse block. Reconnect 120VAC and verify 120VAC at terminal blocks. Check power supply outputs, fan status, and wiring connections to the Densitometer.
Densitometer will not display max OD of 4.00	Verify that the sensor has not been recalibrated on an existing OD greater than zero. (See Note in previous section.) If so, then recalibrate the sensor on an OD zero target. Verify that the sensor and corresponding light covers are clean and clear of obstructions.

3.7 MAINTENANCE GUIDE

3.7.1 System Overview:

In general, beyond routine cleaning, the Sigma Inline Optical Densitometer requires little to no operator intervention. However, as with all instruments instances will occasionally arise where the operator may be called upon to perform detailed maintenance tasks to ensure the proper operation of the device. Figure 25 below gives a maintenance overview of the Densitometer system and its specific subsystem components. This diagram should be consulted whenever a subsystem alteration or repair is required.

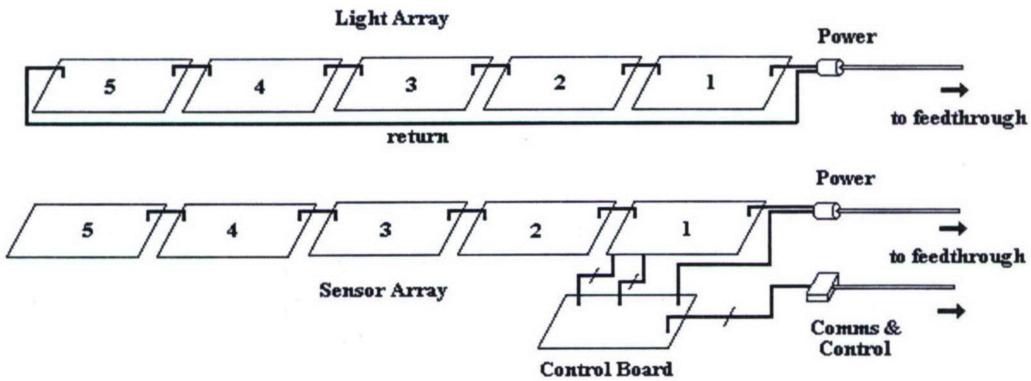

Figure 25. System Overview

3.7.2 Light Gallery

a) Cleaning

The clear light gallery transmit covers should be routinely inspected for obstructions and debris. These covers can be cleaned with a cotton Q-tip and isopropyl alcohol. It should be noted that even if the light transmit or sensor covers are partially obstructed that the device will still function correctly. Calibrating with these obstructions in place is similar to calibrating on a known OD value. That is to say, the light level change caused by these obstructions will be nulled or referenced out upon calibration of the device. The only detriment will be that the maximum optical density capable of being seen will be reduced. This being said, it is clearly preferable to keep the sensor/light covers free of debris. For the first several runs after the initial installation of the device the operator should inspect these covers to gage how often this practice needs to be done. Thereafter a routine schedule

can be set. The physical placement of the Densitometer will greatly affect this cleaning schedule. (See Section 1.2.)

b) Maintenance:

The high intensity LED light gallery (660nm) should require very little operator intervention. The lights themselves should last for years with little ill effects. Array intensity is maintained via a precision current regulator and minor intensity differences from light to light are accounted for through the device's calibration routines. Should an LED fail, the offending light should be removed from the appropriate circuit board and replaced with a new one.

3.7.3 Sensor Array

a) Cleaning:

The clear sensor covers should be routinely cleaned as described in section 2.2.

b) Maintenance:

Sensor failure is rare, but should it occur sensors can be replaced by removing the appropriate sensor cover and inserting a new sensor in place of the failed one. Additional maintenance concerns are primarily power issues. Should a section of the sensor array lose power examine the board-to-board power connections (on the underside of each board) for a loose cable.

3.7.4 Control Board

Beyond loose power and signal interconnections there are few operator maintenance issues when it comes to the control board. One possible intervention issue however, exists in the form of the board's RS-232 level shifting IC. If there is a failure in serial communications and all other corrective avenues have been pursued without success one possible explanation is a failure in the control boards MAX233EP level shifting IC. This IC can be clearly identified on the control board, and as a last resort, can be replaced with a like device. Care should be taken in regards to the IC's orientation if replacement of this device is pursued.

3.7.5 Power Supplies

The operator should consult figure 1-3 when dealing with power supply maintenance issues. A loose wire, bad fuse, or lack of main 120VAC will explain most power supply issues. As with most power supplies of the type used in the Densitometer if a major failure occurs with the supply internal circuitry it is easier to simply replace the supply with another of the same specifications and form factor. Both Condor supplies, and others with the same form factor and specifications are available through numerous electronics suppliers.

3.7.6 Regulator Board

The intensity of high output LED's is a linear function of the current passing through each element. The regulator board located within the power supply cabinet takes advantage of this relationship by fixing the current levels through the light array via a precision current sink and voltage reference. Power is supplied to the light array via a Condor DC supply and then returned from the array to the current sink circuitry, which regulates this current by referencing it to a temperature compensated voltage reference. The current through the regulator is monitored for a failure condition, and if a failure occurs, a control signal is passed to the Densitometer directing it to transmit a Light Array failure signal. A schematic of the regulator board is included later in the manual for troubleshooting and should be consulted if problems with the regulator board are suspected. If the operator or maintenance technician is familiar with component level troubleshooting the various subsystems of the board's architecture can be examined for errors. As a passing note, the technician is directed to examine local power levels set via the three pin regulators first before moving on to the reference, op-amp, BJT follower circuitry. If no familiarity exists along these lines a shotgun approach can be taken, which calls for the replacement of all major IC elements on the board, either as a group or one at a time. If neither approach is desired, a new board can be obtained by contacting Sigma Technologies.

3.7.7 User Interface

The user GUI is an executable program located on the PC supplied with the system. The GUI is essentially independent of the actual Densitometer operations. That is to say, it is merely a program that is in communications with the Densitometer. The GUI may pass commands to the Densitometer and may receive data from the Densitometer, but it has no direct access to the Densitometer's operating system. This means that if the GUI should crash because of PC failure, PC operating system error, or any other cause the Densitometer is still running in operational mode. Restarting the GUI will place the GUI back in communications with the Densitometer and restore the system to normal operational status. (Recalibration does not need to be done as the Densitometer has maintained this data throughout the GUI down time.)

The implications of this arrangement lead to the Sigma Inline Densitometer being a stand alone device able to communicate with any serial device capable of receiving data and transmitting the appropriate command codes (whether this be another PC, a data logger, a PLC, etc.). Two serial interfaces are provided with the Densitometer, one dedicated to the PC provided to be used in conjunction with the supplied GUI and another left uncommitted.

3.7.8 Miscellaneous Notes

The listing below is a series of miscellaneous notes pertaining to operational an maintenance issues regarding the Sigma Inline Densitometer.

i) One of the easiest ways to verify Densitometer operation is to remove the power connection at the light gallery and watch for a display change at the GUI. This quick go/ no-go test is useful in troubleshooting the device. A corollary to this method is to place a dark object over a questionable sensor and look for a display change.

ii) If multiple GUI's are used, or if the Densitometer is communicating with multiple devices, designate one device as a master, which is responsible for transmitting the appropriate command strings. In actuality this is not necessary as the Densitometer will respond to either GUI, but such instances may lead to confusion unless the other two devices are aware of the action taken by the other.

iii) Care should be exercised if the output of the Densitometer is used within a control loop. Control loop time constants should be examined before implementing this arrangement, and more than likely, the output of the Densitometer will have to be filtered (sampled at a slower rate) to put its response inline with other system time constants. Failure to abide by these control system conditions will lead to a destabilization of the implement loop, which more than likely will result in system wide oscillations.

iv) If possible, work on the Densitometer in place. The sectioned covers can prove quite useful in this regard.

v) Physically treat the device as you would any other measuring instrument. The Densitometer is quite study and durable, but jarring impacts or other such occurrences can reduce its lifespan, and more often than not, lead to unnecessary maintenance issues.

3.8 DOCUMENTS-REPLACEMENT PARTS LIST

Table 3 lists a number of replacement parts associated with the Sigma Inline Densitometer

Table 3. Replacement Parts for the Sigma Inline Densitometer

Subsystem	Part	Vendor
Light Array	AND190CRP Ultra-Bright 660nm LED	Newark
Control Board	MAX233EP Dual RS232 level translator	Digi-Key, Newark
Regulator Board	LM7805, LM7812 Three pin regulators	Digi-Key, Newark
Regulator Board	2N3904, SN7408, LF411C, etc.	Digi-Key, Newark
Power Cabinet	HB5-3-OV-A+ 5 VDC linear power supply	Digi-Key
Power Cabinet	HB28-1-A+ 28 VDC linear power supply	Digi-Key
Miscellaneous	Cannon connectors, DB connectors, etc.	Digi-Key, Newark
Sensor Array	Contact Sigma Technologies Int., Inc.	-
Control Board	Contact Sigma Technologies Int., Inc.	-

SECTION 4
CAPACITOR ELECTRODE DESIGN AND FABRICATION

4.1 HEAVY EDGE-THIN ELECTRODE DESIGN

Self-healing properties of metallized capacitors are enhanced significantly by increasing active electrode resistivity (i.e. Ohms/sq.). This has the effect of limiting the current dumped into the breakdown arc and minimizes capacitor damage. The energy of the a clearing event is inversely proportional to the metallized electrode resistance, *therefore the higher resistance electrodes lead to lower local damage* which translates to higher voltages before one or more breakdown events lead to a thermal runaway failure mechanism. However, higher electrode resistance causes a higher capacitor ESR, poor electrode contact and early failure if the capacitor is forced to carry high AC or discharge currents. This can be remedied by depositing heavier metal at the capacitor edge which remains outside the active capacitor area, as illustrated in Figure 26

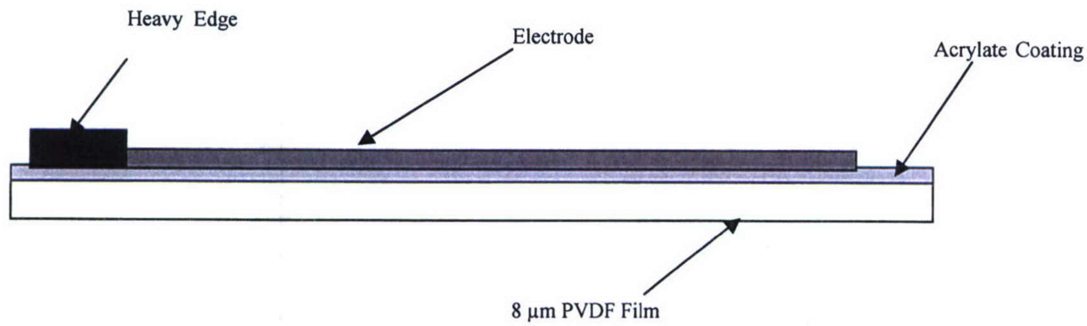

Figure 26 . Schematic Diagram for the Heavy edge-Thin electrode design

A typical mask for implementing the heavy edge/ Thin electrode design is shown in Figure 27

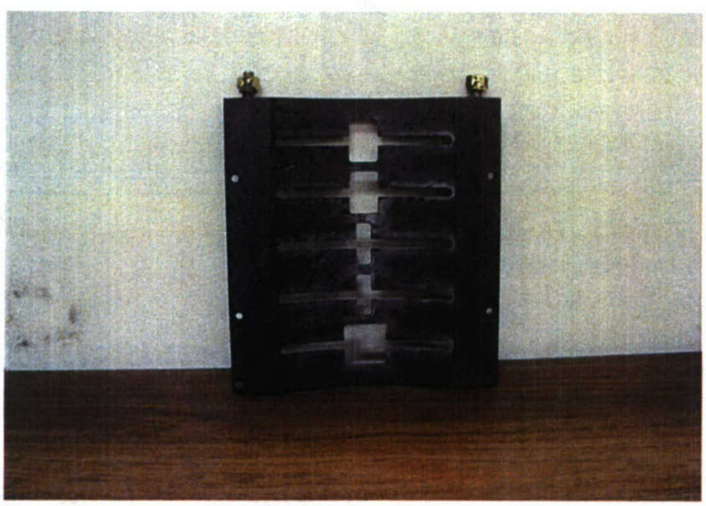

Figure 27. Heavy Edge-Thin Electrode Mask

4.2 ELECTRODE SEGMENTATION

Increased electrode resistivity can alternatively be obtained by segmenting the electrode without decreasing the thickness. This is illustrated by the following FEM analysis of a segmented electrode.

4.2.1 Calculation of the Effective Resistance of a Segmented Electrode

The goal for this task is to estimate the effect of electrode segmentation on the increase of the effective resistance of the electrode. A Finite Element Method (FEM) analysis was carried out. For the sake of illustration, the segmentation pattern is shown in Figure 28. Given the current I, and the initial resistance R_0(=10 Ohms/square) and ground Potential V_0 ,the potential everywhere is the solution of the differential equation:

$$\nabla^2 V=0$$

Considering the particular geometry of Figure 28 , the solution at the extremity, as shown in Figure 29, was found to be V=118.62 V for I=1A. The effective resistance is then simply equal to 118.62 Ohms, a figure that is more than ***10 times*** the initial resistance.

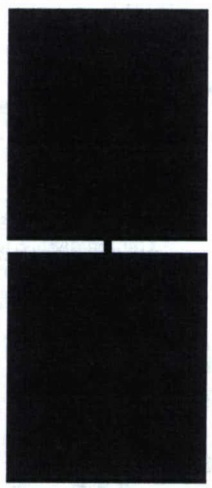

Figure 28. Diagram showing a square shaped segmented electrode design

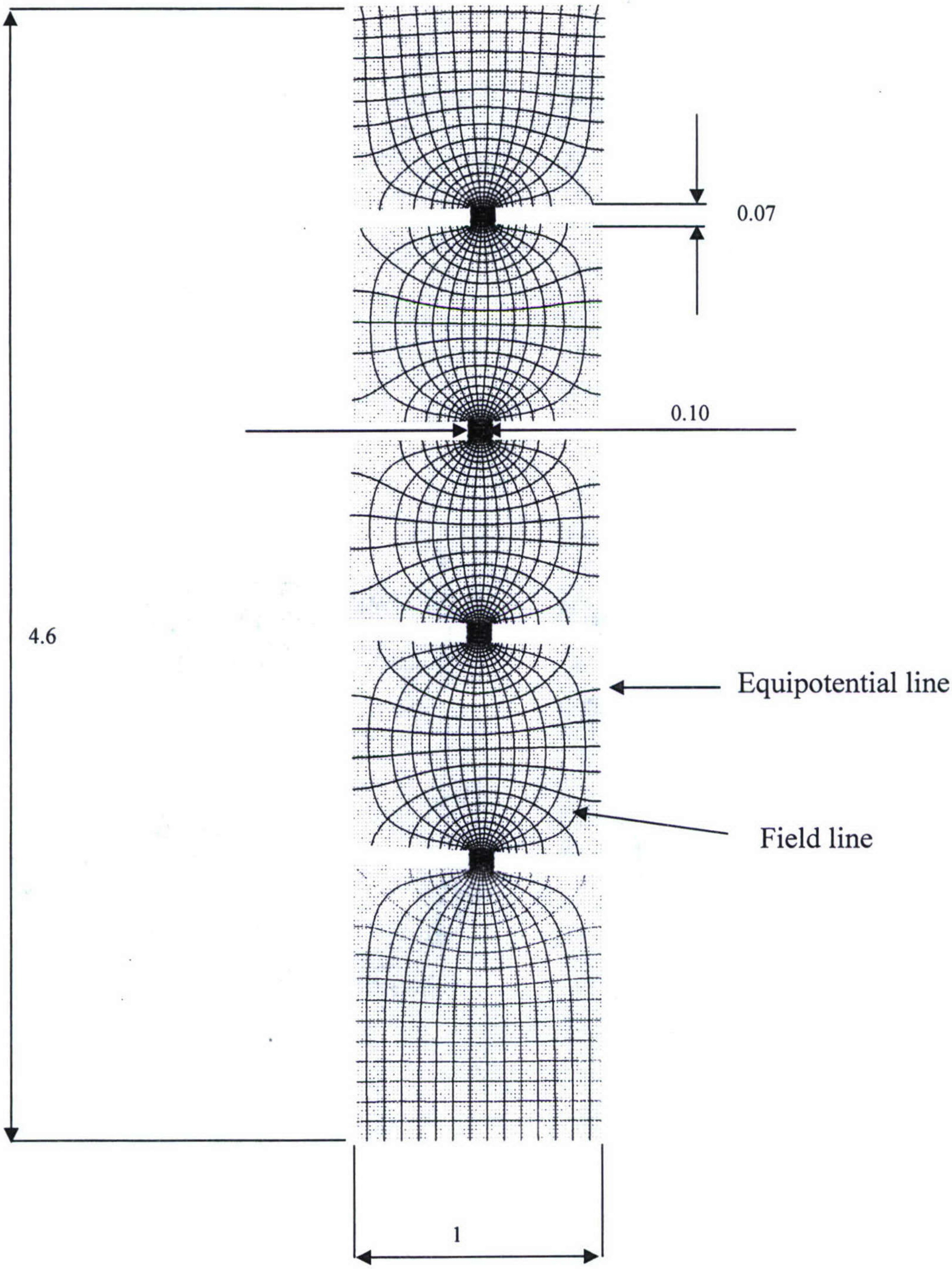

Figure 29. FEM map of a segmented electrode. The dimensions shown are in arbitrary units.

4.2.2 Design Of a System For Making Segmented Electrodes.

The segmented electrode technology was developed a while back to improve the failure mechanism of AC capacitors on high power AC lines. In case of capacitor failure, there will be no catastrophic short.

The electrode segmentation is carried out using an oil printing mechanism. Oil prevents aluminum deposition An offset gravure printing system is be used to print less than 100 angstrom oil layer on the hybrid film prior to the deposition of the aluminum electrode. The resolution of this system is approximately equal to that of an ink printing system, which can lead to demetallized areas with very fine lines and intricate shapes.

Pictures of segmented electrodes and printing systems are shown in Figures 30, and 31 respectively.

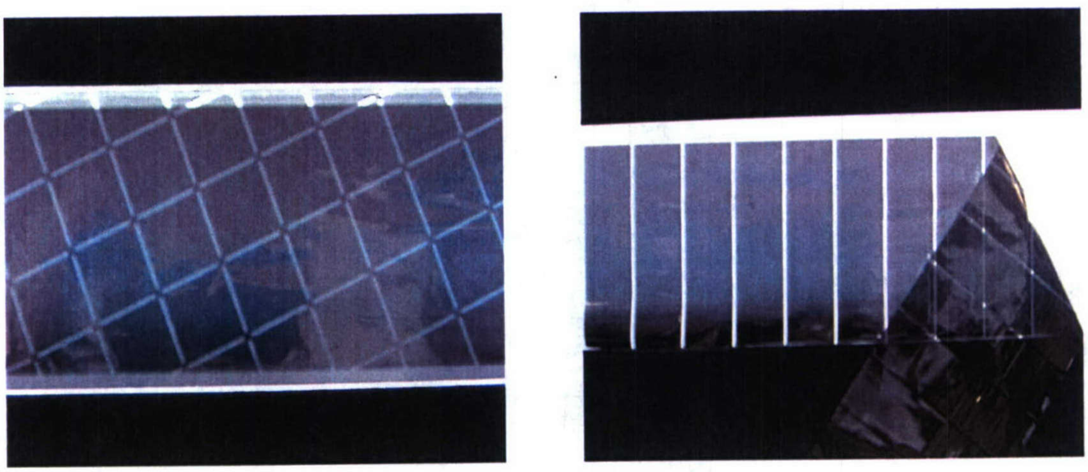

Figure 30. Electrode Segmentation Patterns

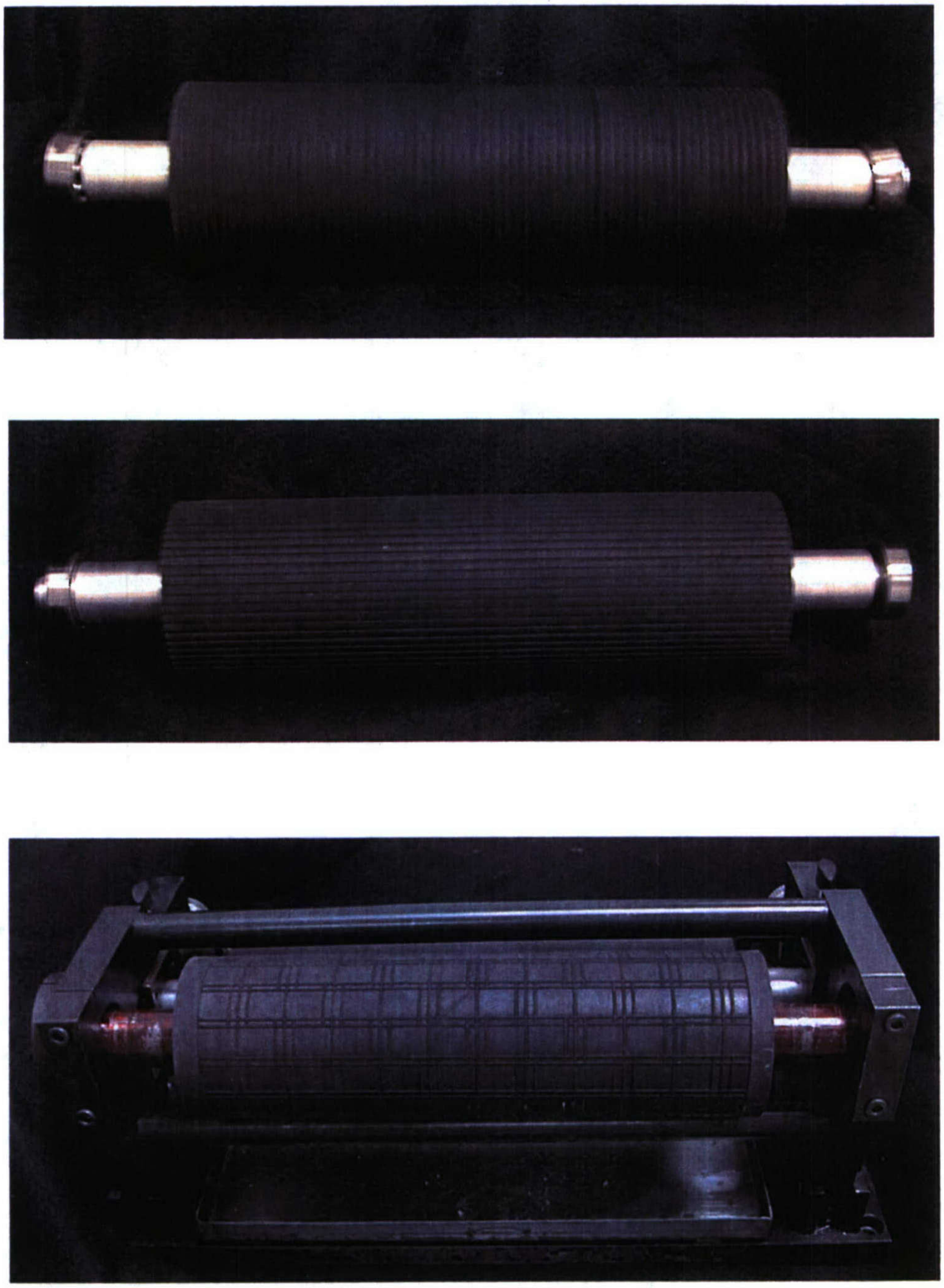

Figure 31. Oil printing mask for making segmented electrodes

SECTION 5
PRODUCTION OF METALLIZED ACRYLATE/FILM CAPACITORS

5.1 ACRYLATE COATINGS

The polymer coatings are based on radiation curable monomers of the general formula

$$R^1\text{-}(\overset{\displaystyle O}{\overset{\|}{OC}}\text{-}\underset{\displaystyle R^2}{C}\text{=}CH)_n$$

wherein R^2 is hydrogen, methyl ethyl, propyl, butyl or pentyl; n is from 2 to 4. R_1 can be a functional group such as amino, cyano, nitrile, halogen, or organometallic. Such difunctional acrylates can be used in combinations with various monofunctional and trifunctional acrylates to optimize the physical and chemical properties of the polymer layers.

Sigma tested various formulations that were developed at Sigma on a continuous basis.

A class representative monomer that is typically used at Sigma is Tri-ethylene-glycol Diacrylate (TEGDA), Formula: $A_C(O\ CH_2\ CH_2)_3$ OAC, where A_c is the acrylate radical (H_2C=CH C=O)-). Other commonly used monomers are TRPGDA and HDODA.

Polymer cross-linking depends greatly on several key parameters that include evaporator and nozzle temperature, monomer feed rate, vacuum chamber pressure, electron gun voltage, reactive gas pressure, drum temperature, and drum speed.

The dielectric constant of each polymer coating is determined from the measurements of the capacitance and coating thickness in stamp capacitors . High dielectric constant polymers developed under this program as well as supplemental research work are summarized in Table 4
The data show that cyano based acrylates have the highest dielectric constant, however and unfortunately they have also the highest dissipation factor. Because of the fact that the dissipation factor is such a critical factor in energy delivery, Sigma will proceed with lower DF acrylates while pursuing research on high dielectric constant-low DF materials.

Table 4. List of the average dielectric properties of select polymer materials which were developed at Sigma

Monomer	C (@1kHz) in pF	DF (@1kHz) (%)	Kappa
405 Cyano Acrylate	491.3	2.84	30.67
406 Cyano Acrylate	424.0	6.46	21.79
231 .Fluoro Acrylate	85.5	1.10	4.19
Sm-11 Polystyrene	377.0	2.93	4.31
233 Fluoro Acrylate	92.5	3.15	3.50
Trpgda	232.0	2.62	3.91
272-Tegda	340.7	1.66	4.36
4028 Bisphenol A Epoxy Diacrylate	41.6	1.90	4.62
C-14: Acrylate Hydro	236.0	2.92	4.30
Sm-10 Polyolefin	284.8	0.63	4.65

5.2 DEPOSITION OF A RADIATION CURABLE ACRYLATE COATING IN VACUUM

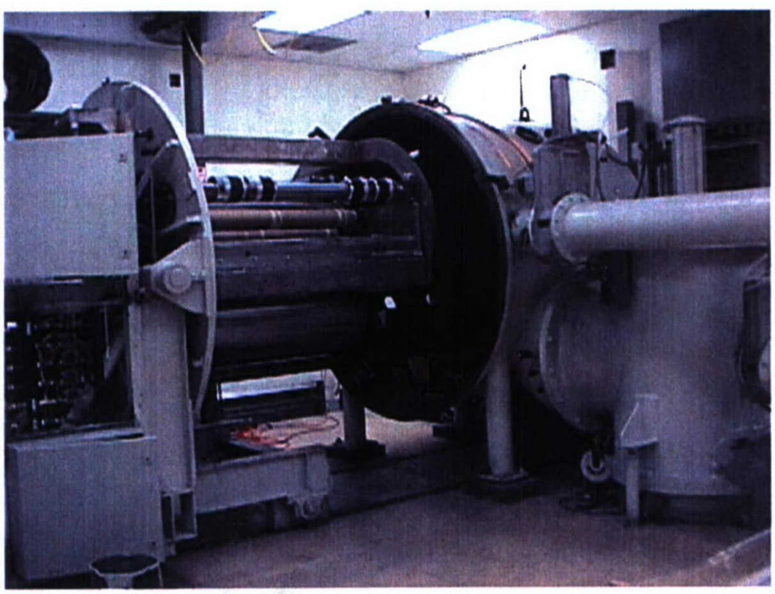

Figure 32. Film Capacitor Pilot Production Machine at Sigma

Hybrid Acrylate/PVDF films are made by depositing a radiation curable acrylate monomer layer on the base film. In this process, liquid monomer is pumped into the vacuum chamber with a precision, computer-controlled delivery system. The monomer is atomized into micro-droplets with the use of an ultrasonic atomizer that is placed in an evaporator which is heated at a temperature that is above the boiling point of the liquid and below its decomposition temperature. In this manner, the micro-droplets of the thermally reactive monomer flash evaporate before the material is cured. The molecular vapor exits the evaporator at supersonic speeds and condenses onto the substrate. The condensed liquid film is cross-linked by exposure to the electron beam to form a uniform polymer layer. To make electrodes, aluminum is thermally evaporated on the cross-linked polymer through a specially designed mask. The drum can rotate at surface speeds as high as 1000 ft/min in order to control the radiation dose or the polymer thickness.

5.3 HEAVY EDGE, THIN ELECTRODE CAPACITOR DESIGN

This design, as shown in Figure 33, has the following advantages:

- Ability to carry high currents
- Prevents thermal runaways
- Fail safe mode

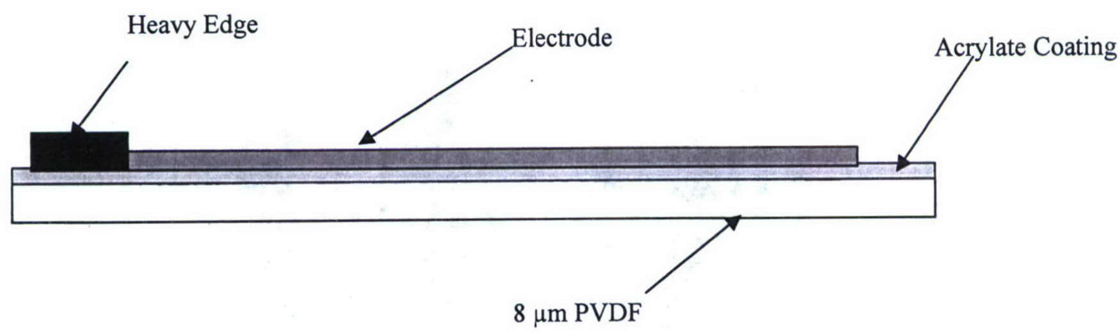

Figure 33. Schematic Diagram for the Heavy edge-Thin electrode design

Electrode Segmentation has the effect of effectively increasing the sheet resistance with decreasing the metal coating thickness, as explained in the part on Segmentation in this report. A picture of the segmented electrode is shown in Figure 34

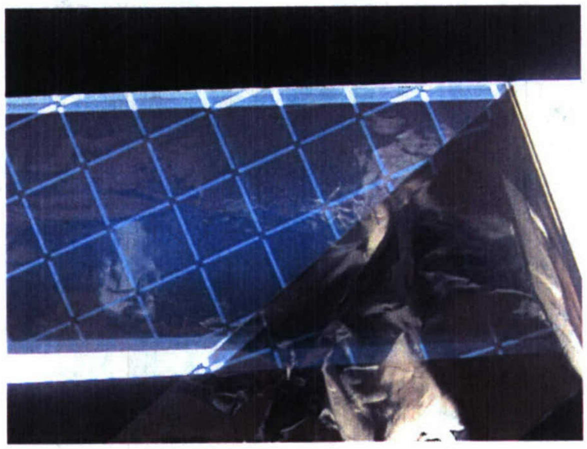

Figure 34. Schematic Diagram for the Heavy edge-Thin electrode design

5.4 ACRYLATE/PP AND ACRYLATE/PET FILM CAPACITORS

OPP and PET capacitors were fabricated as described in Table 5, and pictured in Figure 35. Capacitor physical characteristics are listed in Table 5. Initial capacitor values are listed in Table 6.

Figure 35. Caps from the SB series

Table 5. DTRA PP and PET Hybrid Film Capacitor Characteristics for Lots SB1-6

Series	Diameter (in) O.D.	Core	Length	Film Type	Film Thickness	Segmented	Coated	Rated Capacitance
SB1	0.61	0.2	2.04	PP	3.5μ	No	No	10.0μF
SB2	0.47	0.2	2.04	PP	3.5μ	No	No	5.0μF
SB3	0.47	0.2	2.04	PET	2.5μ	No	Yes	10.0μF
SB4	0.36	0.2	2.04	PET	2.5μ	No	Yes	5.0μF
SB5	0.38	0.2	2.04	PET	2.5μ	Yes	Yes	5.0μF
SB6	0.5	0.2	2.04	PET	2.5μ	Yes	Yes	10.0μF

Table 6. Initial values of capacitors of Lots SB1-6

Series		SB1	SB2	SB3	SB4	SB5	SB6
Cap (μF)	0.1kHz	9.791	5.08	10.139	4.697	4.895	10.048
	1kHz	9.792	5.08	10.114	4.955	4.884	10.028
	10kHz	10.161	5.177	10.432	5.014	4.942	10.351
	40kHz	22.59	7.22	23.285	6.885	6.665	22.74
DF	0.1kHz	0.00041	0.00042	0.00148	0.0015	0.00139	0.00141
	1kHz	0.00158	0.001	0.00466	0.00399	0.00452	0.00524
	10kHz	0.0146	0.0091	0.0224	0.0152	0.024	0.0312
	40kHz	0.152	0.0571	0.185	0.0643	0.114	0.276
ESR (Ω)	0.1kHz	0.066	0.132	0.233	0.487	0.454	0.222
	1kHz	0.026	0.033	0.0735	0.128	0.147	0.0832
	10kHz	0.023	0.028	0.0342	0.0481	0.0771	0.048
	40kHz	0.026	0.031	0.0306	0.037	0.0674	0.0449

5.4.1 Capacitor Electrical Characterization

The first step after fabrication is capacitor clear. Capacitance (Cap), Dissipation Factor (DF), Equivalent Series Resistance (ESR), and Insulation Resistance (IR) are measured again. This set of values is considered as the reference for future measurements, as shown in Tables 7-12. Capacitor clearing is done at 40 Vac.

Table 7. Capacitance, DF, ESR, and IR for lot SB1.

Lot #	Cap #	Cap, μF 1kHz	DF 1kHz	ESR, Ohms 1kHz	Cap, μF 100kHz	DF 100kHz	ESR, Ohms 100kHz	I.R., MΩ 100V, 2 min
SB1	1	9.833	0.00152	0.0246	7.423	0.0570	0.0122	3.4E+04
	2	9.838	0.00156	0.0252	7.395	0.0529	0.0114	2.8E+04
	3	9.712	0.00152	0.0248	0.753	0.0591	0.0124	2.9E+04
	4	9.707	0.00152	0.0248	7.582	0.0540	0.0114	2.8E+04
	5	9.720	0.00151	0.0248	7.533	0.0506	0.0107	2.9E+04
	6	9.784	0.00155	0.0252	7.541	0.0581	0.0126	3.2E+04

7	9.780	0.00156	0.0254	7.620	0.0564	0.0117	2.6E+04
8	9.864	0.00156	0.0252	7.633	0.0509	0.0106	2.6E+04
9	9.746	0.00151	0.0247	7.753	0.0487	0.0100	3.0E+04
10	9.726	0.00153	0.0250	7.288	0.0540	0.0118	2.4E+04
11	9.738	0.00151	0.0247	7.776	0.0467	0.0097	2.8E+04
12	9.780	0.00156	0.0255	7.565	0.0502	0.0105	2.4E+04
13	9.728	0.00155	0.0255	7.504	0.0529	0.0113	2.7E+04
14	9.751	0.00152	0.0249	7.550	0.0529	0.0111	3.0E+04
15	9.800	0.00160	0.0259	7.193	0.0490	0.0109	2.8E+04
16	9.695	0.00155	0.0256	7.499	0.0643	0.0132	3.0E+04
17	9.728	0.00150	0.0246	7.646	0.0437	0.0091	3.0E+04
18	9.742	0.00153	0.0248	7.313	0.0517	0.0113	2.8E+04
19	9.828	0.00156	0.0254	7.603	0.0563	0.0118	3.0E+04
20	9.761	0.00155	0.0253	7.127	0.0513	0.0114	2.5E+04
21	9.717	0.00155	0.0254	7.080	0.0577	0.0128	3.0E+04
22	9.700	0.00151	0.0248	8.002	0.0475	0.0094	2.8E+04
23	9.781	0.00153	0.0249	7.928	0.0452	0.0090	2.7E+04
24	9.818	0.00152	0.0248	7.710	0.0531	0.0108	3.3E+04
25	9.8	0.00155	0.0252	7.8000	0.0505	0.0106	2.7E+04

Table 8. Capacitance, DF, ESR, and IR for Lot SB2

Lot #	Cap #	Cap, µF 1kHz	DF 1kHz	ESR, Ohms 1kHz	C, µF 100kHz	DF 100kHz	ESR, Ohms 100kHz	I.R., MΩ 100V, 2 min
SB2	1	5.071	0.00103	0.0326	4.470	0.0470	0.0168	6.5E+04
	2	5.071	0.00100	0.0314	4.434	0.0435	0.0156	5.5E+04
	3	5.020	0.00101	0.0321	4.319	0.0490	0.0180	6.5E+04
	4	5.010	0.00102	0.0322	4.355	0.0472	0.0172	6.0E+04

5	5.013	0.00099	0.0316	4.393	0.0422	0.0153	7.0E+04
6	4.993	0.00101	0.0322	4.366	0.0435	0.0158	8.5E+04
7	5.049	0.00101	0.0318	4.364	0.0479	0.0174	5.5E+04
8	5.043	0.00101	0.0321	4.316	0.0435	0.0160	7.0E+04
9	5.027	0.00100	0.0316	4.334	0.0489	0.0178	6.5E+04
10	4.993	0.00100	0.0315	4.334	0.0442	0.0162	5.0E+04
11	5.027	0.00101	0.0322	4.338	0.0443	0.0163	6.0E+04
12	5.051	0.00105	0.0334	4.330	0.0515	0.0189	5.5E+04
13	5.045	0.00101	0.0317	4.362	0.0458	0.0166	5.5E+04
14	5.028	0.00102	0.0323	4.378	0.0449	0.0164	8.0E+04
15	5.047	0.00101	0.0321	4.324	0.0460	0.0172	7.5E+04
16	5.029	0.00100	0.0318	4.378	0.0496	0.0180	6.0E+04
17	4.998	0.00099	0.0314	4.407	0.0394	0.0142	5.0E+04
18	5.029	0.00102	0.0323	4.334	0.0413	0.0152	7.0E+04
19	5.025	0.00099	0.0314	4.384	0.0422	0.0153	7.0E+04
20	5.002	0.00099	0.0315	4.256	0.0550	0.0206	4.5E+04
21	5.056	0.00103	0.0326	4.424	0.0452	0.0162	5.5E+04
22	5.022	0.00101	0.0320	4.390	0.0422	0.0153	5.0E+04
23	4.989	0.00100	0.0318	4.317	0.0416	0.0154	7.0E+04
24	4.994	0.00100	0.0319	4.218	0.0524	0.0198	8.0E+04
25	5.083	0.00102	0.0317	4.420	0.0420	0.0152	7.5E+04

Table 9. Capacitance, DF, ESR, and IR for Lot SB3

Lot #	Cap #	Cap, µF 1kHz	DF 1kHz	ESR, Ohms 1kHz	Cap, µF 100kHz	DF 100kHz	ESR, Ohms 100kHz	I.R., MΩ 100V, 2 min
SB3	1	10.095	0.00445	0.0701		0.0514	0.0116	9.5E+03
	2	10.041	0.00441	0.0699	7.085	0.0534	0.0119	1.0E+04
	3	9.986	0.00447	0.0713		0.0428	0.0097	2.4E+02
	4	10.113	0.00445	0.0700		0.0447	0.0095	9.0E+03
	5	10.002	0.00400	0.0700	7.009	0.0568	0.0113	8.5E+03
	6	9.587	0.00427	0.0709		0.0471	0.0106	9.5E+03
	7	10.075	0.00446	0.0704		0.0485	0.0110	8.0E+03
	8	9.986	0.00446	0.0711		0.0460	0.0096	9.0E+03
	9	9.991	0.00439	0.0700		0.0175	0.0042	1.1E+04
	10	10.101	0.00441	0.0696		0.0458	0.0096	1.2E+04
	11	10.106	0.00452	0.0713		0.0549	0.0115	9.5E+03
	12	10.036	0.00442	0.0702		0.0630	0.0135	1.2E+04
	13	10.021	0.00440	0.0699		0.0437	0.0092	1.1E+04
	14	10.091	0.00442	0.0698		0.0617	0.0132	1.0E+04
	15	10.073	0.00443	0.0699		0.0436	0.0085	1.1E+04
	16	10.048	0.00444	0.0704		0.0511	0.0110	9.5E+03
	17	9.986	0.00446	0.0712	6.916	0.0480	0.0103	1.0E+04
	18	10.052	0.00441	0.0698	7.115	0.0387	0.0083	8.5E+03
	19	10.063	0.00450	0.0712		0.0357	0.0090	1.0E+04
	20	10.124	0.00450	0.0708		0.0480	0.0109	9.5E+03
	21	10.116	0.00443	0.0696	7.047	0.0479	0.0108	1.0E+04
	22	10.111	0.00444	0.0699		0.0468	0.0104	1.0E+04
	23	10.162	0.00448	0.0702		0.0508	0.0110	9.0E+03
	24	10.099	0.00452	0.0711		0.0586	0.0138	8.5E+03

Table 10. Capacitance, DF, ESR, and IR for Lot SB4

Lot #	Cap #	Cap, µF 1kHz	DF 1kHz	ESR, Ohms 1kHz	Cap, µF 100kHz	DF 100kHz	ESR, Ohms 100kHz	I.R., MΩ 100V, 2 min
SB4	1	5.139	0.00409	0.127	4.231	0.0357	0.0144	1.3E+04
	2	5.053	0.00403	0.127		0.0412	0.0151	1.4E+04
	3	5.165	0.00412	0.126	4.262	0.0447	0.0174	400
	4	5.104	0.00405	0.126		0.0527	0.0198	1.4E+04
	5	5.040	0.00401	0.127		0.0489	0.0186	1.4E+04
	6	5.001	0.00398	0.127		0.0501	0.0192	1.4E+04
	7	5.027	0.00396	0.125		0.0485	0.0183	1.5E+04
	8	5.058	0.00400	0.126	4.121	0.0331	0.0134	1.6E+04
	9	5.063	0.00399	0.125		0.0427	0.0167	68
	10	5.062	0.00403	0.127		0.0362	0.0149	1.4E+04
	11	5.087	0.00401	0.125		0.0466	0.0171	1.5E+04
	12	5.201	0.00418	0.128		0.0352	0.0140	1.4E+04
	13	5.061	0.00401	0.126	4.241	0.0392	0.0157	1.3E+04
	14	5.179	0.00415	0.127		0.0497	0.0185	1.3E+04
	15	5.095	0.00408	0.128		0.0506	0.0191	1.3E+04
	16	5.118	0.00407	0.127		0.0368	0.0149	1.4E+04
	17	5.038	0.00398	0.126		0.0493	0.0191	1.5E+04
	18	5.106	0.00410	0.128		0.0330	0.0131	1.4E+04
	19	5.174	0.00417	0.128		0.0536	0.0196	1.3E+04
	20	5.105	0.00407	0.127	4.222	0.0403	0.0152	1.4E+04
	21	5.115	0.00408	0.127		0.0419	0.0150	1.5E+04
	22	5.048	0.00399	0.126		0.0513	0.0193	1.4E+04
	23	5.074	0.00411	0.129		0.0432	0.0157	1.4E+04
	24	5.041	0.00394	0.125		0.0416	0.0163	1.5E+04

Table 11. Capacitance, DF, ESR, and IR for Lot SB5

Lot #	Cap #	Cap, µF 1kHz	DF 1kHz	ESR, Ohms 1kHz	C, µF 100kHz	DF 100kHz	ESR, Ohms 100kHz	I.R., MΩ 100V, 2 min
SB5	1	4.864	0.00442	0.145		0.121	0.0450	6.0E+03
	2	4.982	0.00453	0.145	4.283	0.120	0.0438	6.0E+03
	3	4.994	0.00463	0.148		0.127	0.0459	6.40E+03
	4	4.904	0.00443	0.144		0.118	0.0437	6.0E+03
	5	4.788	0.00440	0.146	4.014	0.122	0.0483	6.0E+03
	6	4.971	0.00452	0.144		0.126	0.0474	6.0E+03
	7	5.049	0.00460	0.145		0.123	0.0454	2.5E+02
	8	5.005	0.00457	0.145		0.128	0.0486	6.0E+03
	9	5.022	0.00460	0.146		0.122	0.0469	1.10E+02
	10	4.844	0.00438	0.144		0.118	0.0449	75
	11	4.934	0.00454	0.146	4.105	0.105	0.0365	6.0E+03
	12	4.896	0.00442	0.144		0.119	0.0447	6.0E+03
	13	4.897	0.00460	0.149		0.128	0.0501	6.0E+03
	14	5.044	0.00454	0.143		0.120	0.0450	6.2E+03
	15	4.976	0.00448	0.143	4.200	0.120	0.0448	6.2E+03
	16	4.856	0.00440	0.144		0.128	0.0494	36
	17	4.708	0.00433	0.146		0.118	0.0468	6.1E+03
	18	4.957	0.00453	0.146		0.129	0.0480	6.5E+03
	19	5.028	0.00460	0.146		0.129	0.0488	6.3E+03
	20	4.808	0.00435	0.144	4.054	0.112	0.0417	6.2E+03
	21	4.867	0.00449	0.147		0.116	0.0449	6.0E+03
	22	4.848	0.00442	0.145		0.117	0.0444	6.1E+03

Table 12. Capacitance, DF, ESR, and IR for Lot SB6

Lot #	Cap #	Cap, μF 1kHz	DF 1kHz	ESR, Ohms 1kHz	Cap, μF 100kHz	DF 100kHz	ESR, Ohms 100kHz	I.R., MΩ 100V, 2 min
SB6	1	9.941	0.00507	0.0812	7.493	0.115	0.0241	3.1E+03
	2	10.074	0.00514	0.0811	7.600	0.121	0.0251	3.2E+03
	3	9.859	0.00499	0.0805	7.473	0.122	0.0255	3.20E+03
	4	10.168	0.00515	0.0807	7.792	0.119	0.0241	3.3E+03
	5	10.043	0.00509	0.0807	7.657	0.110	0.0226	3.0E+03
	6	10.075	0.00507	0.0802	7.811	0.121	0.0242	3.2E+03
	7	10.061	0.00508	0.0803	7.745	0.118	0.0240	3.2E+03
	8	10.002	0.00510	0.0811	7.613	0.112	0.0231	3.2E+03
	9	10.023	0.00510	0.0812	7.698	0.115	0.0234	3.10E+03
	10	10.194	0.00516	0.0806	7.550	0.119	0.0250	3.3E+03
	11	10.139	0.00513	0.0806	7.829	0.113	0.0225	3.2E+03
	12	10.044	0.00513	0.0815	7.416	0.117	0.0249	3.1E+03
	13	10.023	0.00506	0.0804	7.597	0.116	0.0240	3.3E+03
	14	10.149	0.00513	0.0806	8.043	0.117	0.0229	3.2E+03
	15	9.940	0.00501	0.0803	7.981	0.103	0.0203	3.2E+03
	16	10.052	0.00511	0.0810	7.505	0.119	0.0250	3.3E+03
	17	10.198	0.00516	0.0805	7.530	0.120	0.0252	3.3E+03
	18	10.138	0.00513	0.0807	7.635	0.124	0.0254	3.3E+03
	19	9.993	0.00506	0.0806	7.942	0.115	0.0229	3.1E+03
	20	10.036	0.00509	0.0807	7.545	0.123	0.0257	3.2E+03
	21	9.963	0.00507	0.0810	7.472	0.122	0.0256	3.4E+03
	22	9.857	0.00504	0.0814	7.483	0.111	0.0232	3.2E+03
	23	9.890	0.00504	0.0811	7.495	0.122	0.0255	3.1E+03
	24	10.052	0.00507	0.0803	7.772	0.121	0.0244	3.2E+03

Capacitor Voltage Breakdown Results

Capacitor breakdown is assumed to occur when capacitance loss is greater than 10% of the original capacitance or when the capacitor fails completely. Measured values for all capacitors lots are shown in Table 13.

Table 13. Variation of Capacitance, DF, and ESR with Voltage for Lot SB1

Lot #	Cap #	Voltage (V DC)	Cap, µF 1kHz	DF 1kHz	ESR, Ω 1kHz	Comments
SB1	1	100	9.833	0.00152	0.0246	
		600	9.162	0.0625	1.08	**Failed**
SB1	2	100	9.842	0.00156	0.0252	
		500	9.678	0.0198	0.326	
		600	9.681	0.0289	0.476	**Failed**
SB1	3	100	9.72	0.00161	0.0262	
		300	9.729	0.00155	0.0254	
		400	9.735	0.00158	0.0258	
		440	9.738	0.00157	0.0258	
		460	9.741	0.00159	0.0260	
		480	9.741	0.0016	0.0261	
		500	9.734	0.00195	0.0317	
		520	9.729	0.00210	0.0345	
		540	9.729	0.00223	0.0365	
		560	9.678	0.0105	0.172	**Failed**
SB1	4	100	9.716	0.00158	0.0259	
		400	9.727	0.00158	0.0258	
		440	9.731	0.00161	0.0265	
		480	9.735	0.00168	0.0274	

		500	9.733	0.00185	0.0290	
		520	9.684	0.00178	0.0291	**Failed**

Table 14. Variation of Capacitance, DF, and ESR with Voltage for Lot SB2

Lot #	**Cap #**	**Voltage (V DC)**	**Cap, µF 1kHz**	**DF 1kHz**	**ESR, Ω 1kHz**	**Comments**
SB2	1	100	5.073	0.00108	0.0340	
		400	5.08	0.00104	0.0324	
		460	5.083	0.00105	0.0327	
		480	5.085	0.00105	0.0326	
		500	5.085	.0.00106	0.0332	
		520	5.076	0.00156	0.0489	
		540	5.078	0.00156	0.0489	
		560	5.079	0.00160	0.0501	
		580	5.080	0.00163	0.0511	
		600	4.803	0.00251	0.0831	**Failed**
SB2	2	100	5.074	0.00103		
		500	5.081	0.00113		
		540	5.084	0.00110		
		560	5.087	0.00110		
		580	5.088	0.00108		
		590	5.088	0.00110		
		600	5.083	0.00114		
		610	5.018	0.155	4.83	**Failed**

Table 15. Variation of Capacitance, DF, and ESR with Voltage for Lot SB3

Lot #	Cap #	Voltage (V DC)	Cap, µF 1kHz	DF 1kHz	ESR, Ω 1kHz	Comments
SB3	1	100	10.067	0.00447	0.0707	
		300	9.653	0.00351	0.0586	**Failed**
SB3	2	100	10.003	0.00444	0.0706	
		140	10.015	0.00446	0.0708	
		180	10.029	0.00448	0.0713	
		200	10.037	0.00455	0.0721	
		220	10.044	0.00449	0.0712	
		240	9.644	0.0035	0.0581	**Failed**
SB3	3	100	9.954	0.00452	0.0723	
		180	9.977	0.00456	0.0727	
		200	9.983	0.00457	0.0730	
		220	9.991	0.00457	0.0728	
		230	9.994	0.00464	0.0740	
		240	9.999	0.00456	0.0725	
		250	10.001	0.00459	0.0731	
		260	9.719	0.00400	0.0661	**Failed**

Table 16. Variation of Capacitance, DF, and ESR with Voltage for Lot SB4

Lot #	Cap #	Voltage (V DC)	Cap, μF 1kHz	DF 1kHz	ESR, Ω 1kHz	Comments
SB4	1	100	5.111	0.00393	0.122	
		200	5.121	0.00408	0.127	
		220	5.123	0.00412	0.128	
		240	5.125	0.00416	0.129	
		260	5.128	0.00419	0.130	
		280	5.131	0.00426	0.132	
		300	5.133	0.00423	0.131	
		320	4.823	0.00316	0.106	**Failed**
SB4	2	100	5.025	0.00405	0.128	
		260	4.714	0.00315	0.108	**Failed**
SB4	3	100	5.112	0.00408	0.127	
		220	5.124	0.00424	0.132	
		240	5.127	0.00462	0.143	
		250	5.128	0.00508	0.158	
		260	5.129	0.00414	0.129	
		270	5.131	0.00414	0.128	
		280	5.132	0.00413	0.128	
		290	5.133	0.00413	0.128	
		300	5.133	0.00413	0.128	
		310	4.780	0.00359	0.121	**Failed**

Table 17. Variation of Capacitance, DF, and ESR with Voltage for Lot SB5

Lot #	Cap #	Voltage (V DC)	Cap, μF 1kHz	DF 1kHz	ESR, Ω 1kHz	Comments
SB5	1	100	4.825	0.00441	0.145	
		300	4.848	0.00446	0.146	
		400	4.859	0.00452	0.148	
		500	4.857	0.00469	0.154	
		600	4.817	0.00506	0.168	
		620	4.683	0.00545	0.185	
		630	4.663	0.00560	0.192	
		640	4.488	0.00578	0.204	
		650	4.458	0.00590	0.211	
		660	4.424	0.00601	0.216	
		670	4.242	0.00614	0.231	>10% Loss
SB5	2	100	4.880	0.00440	0.144	
		600	4.705	0.00505	0.171	
		620	4.562	0.00540	0.188	
		640	4.561	0.00558	0.195	
		660	4.477	0.00585	0.207	
		670	4.206	0.00600	0.227	>10% Loss

Table 18. Variation of Capacitance, DF, and ESR with Voltage for Lot SB6

Lot #	Cap #	Voltage (V DC)	Cap, μF 1kHz	DF 1kHz	ESR, Ω 1kHz	Comments
SB6	1	100	9.880	0.00502	0.0809	
		500	9.876	0.00515	0.0831	
		600	9.870	0.00543	0.0875	
		620	9.736	0.00563	0.0922	
		640	9.717	0.00588	0.0960	
		660	8.911	0.00611	0.109	
		670	8.504	0.00627	0.117	**>10% Loss**
SB6	2	100	10.026	0.00502	0.0797	
		600	9.600	0.00544	0.0900	
		640	9.268	0.00573	0.0988	
		650	8.802	0.00593	0.107	**>10% Loss**

5.4.2 Capacitor Environmental Testing

Capacitors were subjected to an 85 °C /85 %RH for a number of hours till failure. Capacitors were taken out and evaluated at regular time intervals. Results are shown in Tables 19-24.

Table 19. Capacitor values during 85 °C /85 %RH Testing for capacitors of Lot SB1

Capacitor	Cap, (μF)				Time (hrs)
	0.1 kHz	**1kHz**	**10kHz**	**40kHz**	
SB1-20	10.005	10.006	10.194	13.942	2
	10.032	10.031	10.178	13.276	4
	9.858	9.881	9.978	12.619	6
	9.859	9.88	9.946	12.37	8
	10.038	10.036	10.087	12.292	10
	9.849	9.869	10.177	15.657	12
	9.821	9.799	7.998	2.039	77
	9.802	9.716	7.301	1.472	81
	9.794	9.662	6.805	1.202	84
	9.784	8.473	2.602	0.172	108
	DF				**Time (hrs)**
	0.1 kHz	**1kHz**	**10kHz**	**40kHz**	
	0.0005	0.00149	0.0229	0.118	2
	0.00069	0.00355	0.0431	0.203	4
	0.00085	0.00487	0.0539	0.224	6
	0.0009	0.00553	0.0591	0.234	8
	0.00092	0.00581	0.0622	0.248	10
	0.00129	0.00965	0.0947	1.141	12
	0.00641	0.0586	0.415	3.009	77
	0.00803	0.074	0.498	3.399	81
	0.00952	0.0877	0.56	3.65	84
	0.0357	0.275	1.371	8.58	108
	ESR, (Ω)				**Time (hrs)**
	0.1 kHz	**1kHz**	**10kHz**	**40kHz**	
	0.0785	0.0238	0.0358	0.0333	2
	0.109	0.0563	0.0673	0.0583	4
	0.135	0.0786	0.0856	0.0675	6
	0.146	0.0893	0.094	0.0714	8
	0.145	0.0922	0.0977	0.0755	10
	0.207	0.156	0.147	0.126	12
	1.032	0.952	0.703	0.584	77
	1.296	1.21	0.868	0.733	81
	1.538	1.436	0.987	0.844	84
	5.78	4.81	2.91	2.66	108

Table 20. Capacitor values during 85 °C /85 %RH Testing for capacitors of Lot SB2

Capacitor	Cap, (μF)				Time (hrs)
	0.1 kHz	**1kHz**	**10kHz**	**40kHz**	
SB2-18	5.127	5.13	5.182	6.055	2
	5.151	5.15	5.196	5.985	4
	5.099	5.11	5.154	5.865	6
	5.0963	5.107	5.148	5.818	8
	5.158	5.156	5.194	5.826	10
	5.101	5.109	5.221	7.538	12
	5.087	5.052	3.966	2.61	77
	5.507	5.003	3.744	2.312	81
	5.066	4.994	3.6	2.07	84
	5.019	4.099	2.754	1.143	108
	DF				**Time (hrs)**
	0.1 kHz	**1kHz**	**10kHz**	**40kHz**	
	0.000477	0.00984	0.0133	0.0599	2
	0.000463	0.00191	0.0266	0.101	4
	0.00063	0.00239	0.0275	0.119	6
	0.00055	0.00269	0.0304	0.131	8
	0.000568	0.00297	0.0322	0.143	10
	0.000784	0.00517	0.0519	0.321	12
	0.00651	0.0601	0.337	0.933	77
	0.00806	0.0744	0.364	0.982	81
	0.00892	0.0829	0.397	1.03	84
	0.0421	0.229	0.494	1.4	108
	ESR, (Ω)				**Time (hrs)**
	0.1 kHz	**1kHz**	**10kHz**	**40kHz**	
	0.148	0.0304	0.0407	0.0392	2
	0.142	0.0589	0.0693	0.0667	4
	0.196	0.075	0.0846	0.0798	6
	0.172	0.0844	0.0937	0.0881	8
	0.175	0.0917	0.102	5.94	10
	0.248	0.161	0.158	0.154	12
	2.026	1.889	1.214	0.0761	77
	2.521	2.361	1.364	0.861	81
	2.795	2.627	1.516	0.961	84
	13.28	8.44	2.26	1.65	108

Table 21. Capacitor values during 85 °C /85 %RH Testing for capacitors of Lot SB3

Capacitor	Cap, (μF)				Time (hrs)
	0.1 kHz	**1kHz**	**10kHz**	**40kHz**	
SB3-17	10.308	10.261	10.381	14.418	2
	9.86	9.801	9.855	13.078	4
	9.792	9.69	9.059	10.8	6
	9.491	7.775	6.709	7.365	8
	9.056	7.138	6.047	6.494	10
	8.372	6.118	4.784	5.499	12
	0.025	0.0101	0.0046	0.00395	77
	DF				**Time (hrs)**
	0.1 kHz	**1kHz**	**10kHz**	**40kHz**	
	0.00308	0.00371	0.0129	0.0374	2
	0.00443	0.00617	0.0245	0.0706	4
	0.00588	0.0242	0.0758	0.127	6
	0.0462	0.148	0.0998	0.116	8
	0.0558	0.171	0.107	0.139	10
	0.106	0.177	0.222	0.377	12
	1.282	0.907	0.468	0.25	77
	ESR, (Ω)				**Time (hrs)**
	0.1 kHz	**1kHz**	**10kHz**	**40kHz**	
	0.479	0.0571	0.0198	0.0103	2
	0.715	0.1	0.0395	0.0214	4
	0.956	0.397	0.133	0.046	6
	7.7	2.96	0.235	0.0618	8
	9.78	3.7	0.279	0.0837	10
	19.84	4.47	0.704	0.239	12
	30.8E6	7.85E6	1.33E6	2.21E5	77

Table 22. Capacitor values during 85 °C /85 %RH Testing for capacitors of Lot SB4

Capacitor	Cap, (μF)				Time (hrs)
	0.1 kHz	**1kHz**	**10kHz**	**40kHz**	
SB4-23	5.269	5.245	5.254	6.099	2
	4.886	4.856	4.842	5.393	4
	4.86	4.826	4.704	4.79	6
	4.763	4.121	2.355	0.843	8
	4.28	1.77	0.631	0.222	10
	3.926	1.473	0.485	0.145	12
	0.0015	0.0018	0.0015	0.0015	77
	DF				**Time (hrs)**
	0.1 kHz	**1kHz**	**10kHz**	**40kHz**	
	0.00283	0.00406	0.0117	0.0281	2
	0.00452	0.00663	0.0267	0.747	4
	0.00502	0.0128	0.0802	0.198	6
	0.0344	0.233	0.595	1.397	8
	0.182	0.716	0.93	1.55	10
	0.206	0.79	1.026	1.916	12
	3.57	0.98	0.146	0.045	77
	ESR, (Ω)				**Time (hrs)**
	0.1 kHz	**1kHz**	**10kHz**	**40kHz**	
	0.855	0.122	0.0356	0.0183	2
	1.471	0.217	0.0878	0.0548	4
	1.646	0.423	0.27	0.158	6
	11.45	8.54	2.967	2.236	8
	4.224	42.64	12.57	8.119	10
	79.95	52.59	16.39	11.25	12
	-----	45.2E6	1.5E6	1.28E5	77

Table 23. Capacitor values during 85 °C /85 %RH Testing for capacitors of Lot SB5

Capacitor	Cap, (μF)				Time
	0.1 kHz	**1kHz**	**10kHz**	**40kHz**	**(hrs)**
SB5-7	5.223	5.203	5.214	6.019	2
	5.186	5.167	5.169	5.842	4
	5.241	5.218	5.17	5.598	6
	5.243	5.217	5.058	5.433	8
	5.169	5.143	4.867	6.21	10
	5.175	5.139	4.812	6.707	12
	0.683	0.669	0.648	0.639	77
	DF				**Time**
	0.1 kHz	**1kHz**	**10kHz**	**40kHz**	**(hrs)**
	0.00241	0.00465	0.0216	0.0758	2
	0.00262	0.00551	0.0294	0.103	4
	0.00314	0.00774	0.0483	0.121	6
	0.00358	0.0115	0.0621	0.114	8
	0.00384	0.017	0.0721	0.112	10
	0.00455	0.0237	0.0887	0.216	12
	0.0211	0.019	0.061	0.166	77
	ESR, (Ω)				**Time**
	0.1 kHz	**1kHz**	**10kHz**	**40kHz**	**(hrs)**
	0.737	0.142	0.066	0.05	2
	0.802	0.17	0.0904	0.0692	4
	0.951	0.235	0.148	0.085	6
	1.086	0.35	0.195	0.0826	8
	5.169	0.526	0.235	0.0848	10
	1.399	0.732	0.292	0.122	12
	48.5	4.49	1.49	1.01	77

Table 24. Capacitor values during 85 °C /85 %RH Testing for capacitors of Lot SB6

Capacitor	Cap, (μF)				Time (hrs)
	0.1 kHz	1kHz	10kHz	40kHz	
SB6-11	10.513	10.482	10.617	14.755	2
	10.527	10.493	10.612	14.472	4
	10.607	10.569	10.627	14.198	6
	10.576	10.537	10.554	14.029	8
	10.425	10.388	10.434	13.715	10
	10.325	10.29	10.686	28.157	12
	4.368	4.323	4.347	5.961	77
	DF				**Time (hrs)**
	0.1 kHz	**1kHz**	**10kHz**	**40kHz**	
	0.00201	0.00378	0.021	0.0867	2
	0.00233	0.00442	0.0247	0.0995	4
	0.00267	0.00534	0.0323	0.102	6
	0.00281	0.00594	0.0326	0.098	8
	0.00258	0.00548	0.0304	0.0985	10
	0.00287	0.00793	0.0544	0.809	12
	0.0101	0.0104	0.0364	0.165	77
	ESR, (Ω)				**Time (hrs)**
	0.1 kHz	**1kHz**	**10kHz**	**40kHz**	
	0.304	0.0573	0.0314	0.0232	2
	0.353	0.067	0.0371	0.0271	4
	0.401	0.0802	0.0483	0.0282	6
	0.423	0.09	0.0491	0.0275	8
	0.394	0.084	0.0462	0.0284	10
	0.443	0.122	0.0808	0.0691	12
	3.64	0.384	0.133	0.107	77

In this environmental test, capacitors are thermally cycled between -65 and 85 °C. Results are shown in Tables 25-30.

Table 25. Capacitance values during -65- +85 °C Testing for capacitors of Lot SB1

Capacitor	Cap (µF) 0.1kHz	1kHz	10kHz	100kHz	Temp (°C)
SB1-21	9.75	9.74	9.76	10.9	30
	9.83	9.83	9.85	11.1	-65
	9.85	9.85	9.86	11.2	-55
	9.85	9.85	9.87	11.2	-45
	9.85	9.85	9.86	11.2	-35
	9.84	9.84	9.86	11.2	-25
	9.83	9.83	9.84	10.9	-15
	9.82	9.82	9.83	10.8	-5
	9.81	9.8	9.82	10.8	5
	9.79	9.79	9.81	10.9	15
	9.78	9.78	9.79	10.9	25
	9.76	9.76	9.78	10.8	35
	9.75	9.75	9.76	10.8	45
	9.74	9.74	9.75	10.8	55
	9.73	9.72	9.74	10.8	65
	9.72	9.71	9.73	10.8	75
	9.71	9.71	9.72	10.8	85
	9.74	9.74	9.75	11	30

Capacitor	DF 0.1kHz	1kHz	10kHz	100kHz	Temp (°C)
SB1-21	0	0.025	0.35	1.91	30
	0	0.004	0.202	1.39	-65
	0	0.001	0.194	1.42	-55
	0	0.002	0.195	1.42	-45
	0	0.004	0.0204	1.51	-35
	0	0.004	0.217	1.46	-25
	0	0.005	0.24	1.31	-15
	0	0.008	0.251	2.54	-5
	0	0.01	0.275	2.67	5
	0	0.013	0.288	2.43	15
	0	0.015	0.312	2.65	25
	0	0.02	0.343	3.19	35
	0	0.026	0.356	3.14	45
	0	0.029	0.378	3.82	55
	0	0.031	0.394	4.51	65
	0	0.033	0.416	4.78	75
	0	0.035	0.432	5.31	85
	0	0.029	0.377	2.37	30

Capacitor	ESR, (Ohms) 0.1kHz	1kHz	10kHz	100kHz	Temp (°C)
SB1-21	0	0.004	56	0.00277	30

	0	0.001	0.003	0.00198	-65
	0	0	0.003	0.002	-55
	0	0	0.0031	0.00202	-45
	0	0	0.0033	0.00214	-35
	0	0.001	0.0035	0.00208	-25
	0	0.001	0.0039	0.00188	-15
	0	0.001	0.0042	0.00369	-5
	0	0.002	0.0043	0.00382	5
	0	0.002	0.0046	0.0036	15
	0	0.003	0.0051	0.00393	25
	0	0.003	0.0054	0.00464	35
	0	0.004	0.0058	0.00466	45
	0	0.005	0.0061	0.00575	55
	0	0.005	0.0065	0.00664	65
	0	0.006	0.0068	0.00707	75
	0	0.006	0.0071	0.00782	85
	0	0.005	0.0062	0.00349	30

Table 26. Capacitance values during -65- +85 °C Testing for capacitors of Lot SB2

Capacitor	Cap, (μF)				Temp
	0.1kHz	1kHz	10kHz	100kHz	(°C)
SB2-16	5.03	5.03	5.04	5.41	30
	5.08	5.08	5.08	5.42	-65
	5.08	5.08	5.09	5.42	-55
	5.08	5.08	5.09	5.42	-45
	5.08	5.08	5.08	5.42	-35
	5.07	5.07	5.08	5.42	-25
	5.07	5.07	5.07	5.32	-15
	5.06	5.06	5.06	5.31	-5
	5.05	5.05	5.06	5.31	5
	5.05	5.05	5.05	5.3	15
	5.04	5.04	5.04	5.3	25
	5.04	5.03	5.04	5.31	35
	5.03	5.03	5.03	5.3	45
	5.03	5.02	5.03	5.29	55
	5.02	5.02	5.02	5.28	65
	5.01	5.01	5.02	5.28	75
	5.01	5.01	5.01	5.27	85
	5.04	5.04	5.04	5.31	30
Capacitor	**DF**				**Temp**
	0.1kHz	**1kHz**	**10kHz**	**100kHz**	**(°C)**
SB2-16	0	0.032	0.328	3.09	30
	0	0.018	0.236	2.1	-65
	0	0.017	0.232	1.88	-55
	0	0.018	0.232	1.93	-45

0	0.017	0.241	2.03	-35
0	0.019	0.25	2.1	-25
0	0.02	0.263	2.23	-15
0	0.02	0.274	2.47	-5
0	0.021	0.287	2.56	5
0	0.025	0.298	2.82	15
0	0.026	0.314	3.16	25
0	0.031	0.324	2.81	35
0	0.034	0.336	3.12	45
0	0.036	0.352	3.45	55
0	0.037	0.363	3.71	65
0	0.04	0.372	3.73	75
0	0.037	0.383	4.08	85
0	0.036	0.348	2.76	30

Capacitor	ESR, (Ohms)				Temp
	0.1kHz	1kHz	10kHz	100kHz	(°C)
SB2-16	0	0.01	0.0104	0.0091	30
	0	0.005	0.0074	0.00611	-65
	0	0.005	0.0073	0.00558	-55
	0	0.005	0.0073	0.00558	-45
	0	0.006	0.0075	0.00601	-35
	0	0.006	0.0079	0.00622	-25
	0	0.006	0.0084	0.00668	-15
	0	0.007	0.0087	0.00741	-5
	0	0.007	0.009	0.00772	5
	0	0.007	0.0094	0.0084	15
	0	0.009	0.0098	0.00941	25
	0	0.01	0.0103	0.00842	35
	0	0.011	0.0107	0.00931	45
	0	0.011	0.0111	0.0104	55
	0	0.011	0.0116	0.0112	65
	0	0.013	0.0119	0.0112	75
	0	0.012	0.0122	0.0123	85
	0	0.011	0.011	0.00816	30

Table 27. Capacitance values during -65- +85 °C Testing for capacitors of Lot SB3

Capacitor	Cap, (µF)				Temp
	0.1kHz	1kHz	10kHz	100kHz	(°C)
SB3-15	10.1	10.1	10	11.2	30
	9.77	9.63	9.5	10.4	-65
	9.7	9.56	9.44	10.3	-55
	9.69	9.54	9.43	10.4	-45
	9.71	9.57	9.45	10.4	-35

9.76	9.63	9.5	10.4	-25
9.82	9.7	9.56	10.3	-15
9.88	9.76	9.63	10.5	-5
9.92	9.83	9.7	10.6	5
9.96	9.89	9.77	10.5	15
10	9.94	9.84	10.6	25
10	9.99	9.91	10.6	35
10.1	10	9.97	10.7	45
10.1	10.1	10	10.8	55
10.1	10.1	10.1	10.9	65
10.2	10.1	10.1	11	75
10.2	10.2	10.2	11.1	85
10.2	10.2	10.1	11.1	30

Capacitor	DF				Temp
	0.1kHz	1kHz	10kHz	100kHz	(°C)
SB3-15	0.091	0.302	0.91	3.54	30
	0.79	0.992	1.03	0.97	-65
	0.874	0.976	0.96	0.671	-55
	0.885	0.967	0.95	1.03	-45
	0.863	0.984	0.996	1.33	-35
	0.804	0.998	1.07	1.08	-25
	0.707	0.976	1.16	1.05	-15
	0.604	0.916	1.21	1.29	-5
	0.491	0.83	1.24	1.63	5
	0.379	0.721	1.23	2.24	15
	0.265	0.592	1.17	3.18	25
	0.172	0.462	1.08	4.2	35
	0.113	0.354	0.979	4.12	45
	0.075	0.26	0.877	4.2	55
	0.055	0.19	0.777	4.43	65
	0.047	0.146	0.69	4.63	75
	0.048	0.124	0.635	5.03	85
	0.058	0.161	0.687	2.82	30

Capacitor	ESR, (Ohms)				Temp
	0.1kHz	1kHz	10kHz	100kHz	(°C)
SB3-15	0.14	0.048	0.0144	0.00502	30
	1.29	0.164	0.0174	0.00138	-65
	1.43	0.163	0.0162	0.0011	-55
	1.46	0.161	0.0159	0.0015	-45
	1.42	0.164	0.0167	0.00204	-35
	1.31	0.165	0.0179	0.00171	-25
	1.15	0.161	0.0192	0.00163	-15
	0.97	0.149	0.002	0.00191	-5

0.8	0.134	0.0203	0.00246	5
0.6	0.116	0.02	0.00341	15
0.42	0.095	0.0189	0.00482	25
0.27	0.074	0.0173	0.00631	35
0.18	0.056	0.0156	0.00601	45
0.12	0.041	0.0139	0.00619	55
0.09	0.03	0.0122	0.00644	65
0.07	0.023	0.0109	0.00665	75
0.08	0.019	0.0099	0.00719	85
0.09	0.025	0.0108	0.00406	30

Table 28. Capacitance values during -65- +85 °C Testing for capacitors of Lot SB4

Capacitor	Cap, (μF)				Temp
	0.1kHz	1kHz	10kHz	100kHz	(°C)
SB4-12	5.22	5.2	5.18	5.45	30
	5.07	5	4.92	5.12	-65
	5.03	4.95	4.88	5.08	-55
	5.02	4.94	4.87	5.08	-45
	5.03	4.96	4.88	5.09	-35
	5.06	4.98	4.91	5.11	-25
	5.09	5.02	4.94	5.13	-15
	5.11	5.05	4.98	5.18	-5
	5.14	5.09	5.02	5.21	5
	5.16	5.12	5.06	5.19	15
	5.18	5.15	5.09	5.22	25
	5.19	5.17	5.13	5.27	35
	5.21	5.19	5.16	5.31	45
	5.22	5.21	5.19	5.35	55
	5.24	5.23	5.21	5.39	65
	5.26	5.25	5.24	5.44	75
	5.28	5.27	5.27	5.48	85
	5.25	5.24	5.23	5.42	30

Capacitor	DF				Temp
	0.1kHz	1kHz	10kHz	100kHz	(°C)
SB4-12	0.087	0.305	0.987	4.58	30
	0.776	1.07	1.28	3.09	-65
	0.89	1.08	1.19	2.85	-55
	0.915	1.08	1.17	2.87	-45
	0.883	1.09	1.21	3.06	-35
	0.818	1.08	1.28	3.23	-25
	0.726	1.05	1.35	3.21	-15
	0.615	0.977	1.4	3.7	-5
	0.496	0.874	1.41	3.86	5
	0.373	0.751	1.37	4	15

	0.254	0.613	1.29	4.45	25
	0.167	0.482	1.19	4.75	35
	0.11	0.368	1.07	4.83	45
	0.076	0.275	0.96	4.94	55
	0.056	0.21	0.855	4.88	65
	0.048	0.167	0.765	4.85	75
	0.057	0.148	0.701	5.01	85
	0.067	0.205	0.823	4.23	30

Capacitor	**ESR, (Ohms)**				**Temp**
	0.1kHz	**1kHz**	**10kHz**	**100kHz**	**(°C)**
SB4-12	0.26	0.093	0.0303	0.0134	30
	2.43	0.341	0.0416	0.00957	-65
	2.81	0.348	0.039	0.00886	-55
	2.9	0.347	0.0382	0.00897	-45
	2.79	0.349	0.0394	0.00955	-35
	2.58	0.347	0.0416	0.0101	-25
	2.29	0.333	0.0434	0.00995	-15
	1.92	0.308	0.0447	0.0114	-5
	1.54	0.274	0.0447	0.0118	5
	1.15	0.234	0.0433	0.0122	15
	0.8	0.19	0.0404	0.0136	25
	0.52	0.149	0.037	0.0141	35
	0.33	0.112	0.033	0.0144	45
	0.23	0.084	0.0294	0.0146	55
	0.17	0.064	0.0261	0.0144	65
	0.15	0.051	0.0232	0.0142	75
	0.17	0.045	0.0212	0.0145	85
	0.21	0.062	0.0251	0.0124	30

Table 29. Capacitance values during -65- +85 °C Testing for capacitors of Lot SB5

Capacitor	**Cap, (μF)**				**Temp**
	0.1kHz	**1kHz**	**10kHz**	**100kHz**	**(°C)**
SB5-20	4.77	4.76	4.74	4.87	30
	4.67	4.61	4.54	4.65	-65
	4.63	4.57	4.51	4.62	-55
	4.62	4.56	4.51	4.62	-45
	4.63	4.57	4.51	4.63	-35
	4.65	4.59	4.53	4.64	-25
	4.67	4.62	4.56	4.64	-15
	4.7	4.65	4.59	4.69	-5
	4.71	4.67	4.62	4.71	5

	4.73	4.7	4.65	4.69	15
	4.75	4.72	4.68	4.73	25
	4.76	4.74	4.71	4.74	35
	4.77	4.76	4.76	4.77	45
	4.78	4.77	4.75	4.8	55
	4.79	4.79	4.77	4.83	65
	4.81	4.8	4.79	4.86	75
	4.82	4.82	4.81	4.88	85
	4.8	4.8	4.78	4.86	30

Capacitor	DF				Temp
	0.1kHz	1kHz	10kHz	100kHz	(°C)
SB5-20	0.075	0.351	1.74	13.3	30
	0.657	0.986	1.84	10.2	-65
	0.765	1	1.75	9.84	-55
	0.781	1	1.73	9.92	-45
	0.762	1.01	1.76	10	-35
	0.708	1.01	1.83	10.2	-25
	0.622	0.978	1.9	10.3	-15
	0.524	0.913	1.96	11	-5
	0.417	0.824	1.99	11.3	5
	0.31	0.719	1.98	11.8	15
	0.214	0.604	1.94	12.1	25
	0.139	0.491	1.87	12.8	35
	0.092	0.396	1.8	13.4	45
	0.064	0.317	1.72	13.6	55
	0.049	0.262	1.64	14	65
	0.044	0.228	1.58	14.3	75
	0.054	0.213	1.55	14.7	85
	0.056	0.253	1.61	13.3	30

Capacitor	ESR, (Ohms)				Temp
	0.1kHz	1kHz	10kHz	100kHz	(°C)
SB5-20	0.25	0.117	0.0584	0.0428	30
	2.23	0.34	0.0643	0.0346	-65
	2.62	0.35	0.0615	0.0336	-55
	2.69	0.349	0.061	0.0338	-45
	2.62	0.351	0.0621	0.0342	-35
	2.41	0.349	0.0642	0.0347	-25
	2.12	0.337	0.0665	0.035	-15
	1.78	0.313	0.0682	0.0368	-5
	1.42	0.281	0.0687	0.0376	5
	1.05	0.244	0.0679	0.0396	15
	0.71	0.204	0.066	0.0402	25
	0.47	0.165	0.0633	0.0422	35

0.32	0.133	0.0604	0.0438	45
0.21	0.106	0.0574	0.0444	55
0.17	0.087	0.0547	0.0453	65
0.15	0.076	0.0526	0.0459	75
0.17	0.07	0.0512	0.0468	85
0.19	0.084	0.0535	0.0428	30

Table 30. Capacitance values during -65- +85 °C Testing for capacitors of Lot SB6

Capacitor	Cap, (μF)				Temp
	0.1kHz	1kHz	10kHz	100kHz	(°C)
SB6-5	10	10	9.98	11	30
	9.82	9.7	9.56	10.4	-65
	9.73	9.59	9.47	10.3	-55
	9.69	9.56	9.44	10.3	-45
	9.71	9.58	9.45	10.3	-35
	9.75	9.62	9.5	10.3	-25
	9.8	9.68	9.55	10.1	-15
	9.85	9.74	9.61	10.2	-5
	9.89	9.8	9.68	10.3	5
	9.93	9.86	9.76	10.3	15
	9.97	9.92	9.83	10.4	25
	10	9.96	9.89	10.5	35
	10	10	9.95	10.5	45
	10.1	10	10	10.6	55
	10.1	10.1	10.1	10.7	65
	10.1	10.1	10.1	10.7	75
	10.2	10.2	10.1	10.8	85
	10.1	10.1	10.1	10.8	30

Capacitor	DF				Temp
	0.1kHz	1kHz	10kHz	100kHz	(°C)
SB6-5	0.079	0.354	1.79	14.3	30
	0.637	0.983	1.85	10	-65
	0.782	1.02	1.74	9.55	-55
	0.817	1.02	1.71	9.68	-45
	0.8	1.02	1.74	9.82	-35
	0.742	1.03	1.82	9.93	-25
	0.659	1	1.91	1.09	-15
	0.559	0.941	1.98	10.8	-5
	0.448	0.852	2.02	11.1	5
	0.334	0.74	2.03	12.4	15
	0.229	0.617	1.99	12.5	25
	0.148	0.502	1.93	13.5	35

0.1	0.399	1.85	14.3	45
0.068	0.317	1.78	14.8	55
0.053	0.261	1.71	15.8	65
0.049	0.228	1.66	16.3	75
0.056	0.21	1.63	16.8	85
0.058	0.235	1.64	14	30

Capacitor	ESR, (Ohms)				Temp
	0.1kHz	1kHz	10kHz	100kHz	(°C)
SB6-5	0.13	0.056	0.0286	0.0202	30
	1.03	0.161	0.0309	0.0152	-65
	1.28	0.169	0.0292	0.0147	-55
	1.34	0.169	0.0287	0.0148	-45
	1.31	0.17	0.0294	0.0151	-35
	1.21	0.17	0.0305	0.0152	-25
	1.08	0.165	0.0318	0.017	-15
	0.91	0.154	0.0328	0.0168	-5
	0.72	0.138	0.0333	0.0169	5
	0.54	0.12	0.0331	0.0188	15
	0.37	0.099	0.0322	0.0187	25
	0.24	0.08	0.0309	0.0201	35
	0.16	0.064	0.0296	0.0211	45
	0.11	0.05	0.0282	0.0217	55
	0.08	0.041	0.027	0.023	65
	0.07	0.036	0.0261	0.0236	75
	0.08	0.033	0.0255	0.0241	85
	0.09	0.037	0.0258	0.0202	30

5.4.3 Energy Density

Testing Procedure:

The capacitor is charged via a constant current (16 ma) power supply to a series of maximum voltages. In each case, the capacitor is then discharged through a given series resistor with the resulting voltage drop over this resistor being captured on a storage oscilloscope. The curve is then digitized and plotted (Figure 36).

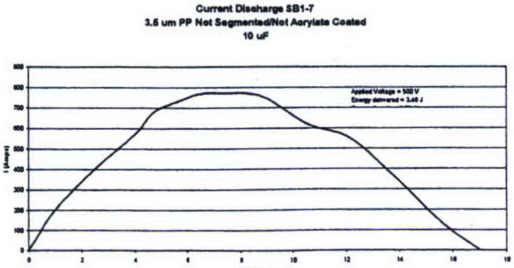

Figure 36. Typical Capacitor discharge curve. The area under the curve is the charge delivered to the load

The charge stored is given by

$$Q = \int I dt$$
$$C = Q/V$$

Where

V = Applied voltage, I=current (as measured), C=Capacitance

The volume energy density, Ud, is given by:

$$Ud=(Q^2/2C)/Volume=(QV/2)/Volume$$

Similarly, the mass energy density, Um, is:

$$Um=(Q^2/2C)/mass=(QV/2)/mass$$

A summary of average values for the energy densities in the capacitors of Batch 1, 2, 3, and 4 is shown in the Table 31 .

Table 31. Maximum Energy density in the SB caps series.

Capacitor Series	**Film Type**	**Film Thickness**	**Segmented**	**Coated**	**Voltage (V)**	**Energy (J/cc)**
SB1	PP	3.5µ	No	No	500	0.716
SB2	PP	3.5µ	No	No	400	0.337
SB3	PET	2.5µ	No	Yes	200	0.105
SB4	PET	2.5µ	No	Yes	200	0.194
SB5	PET	2.5µ	Yes	Yes	450	1.257
SB6	PET	2.5µ	Yes	Yes	450	2.560

The results in Table 31 show that a record energy density (2.5 J/cc) has been established in segmented electrode acrylated PET films capacitors.

5.5 ACRYLATE/PVDF FILM CAPACITORS

Figure 37. DTRA 8 mic Acrylate/PVDF caps

5.5.1 Capacitors Values, Voltage Breakdown, and Energy Density

All the values obtained are summarized in the following table 4.

Table 32. Capacitor values, dissipation factor (df), and ESR at 0.02, 1, and 10 kHz.

PVDF Capacitor Characteristics						
D cap Inch	D core inch	Height inch	total V cc	core V cc	Eff. V cc	MASS grams
1.32	0.38	1.5	33.621	2.7863	30.8346	59.9

BATCH	grp1 coated pair4				SAMPLE		tl				
V Volts	20 hz c uF	20 hz df %	20 hz esr Ω	1 khz c uF	1 khz df %	1 khz esr Ω	10khz c uF	10khz df %	10khz esr Ω	energy density (J/cc)	energy density (J/g)
3500	23.63	1.45	0.98	23.15	2.32	0.15	22.87	8.35	58.1	4.30	2.42

SAMPLE	9								Ω		
V Volts	20 hz c uF	20 hz df %	20 hz esr Ω	1 khz c uF	1 khz df %	1 khz esr Ω	10khz c uF	10khz df %	10khz esr Ω	energy density (J/cc)	energy density (J/g)
0	24.19	1.27	4.19	23.56	1.5	0.1016	23.3	4.47	0.0305	0.00	0.00
500	24.57	1.4	4.55	23.87	1.6	0.1072	23.6	4.59	0.0309	0.09	0.05
1000	26.92	2.53	7.31	25.39	2.37	0.145	24.77	5.38	0.0346	0.40	0.22
1500	26.95	2.44	7.16	25.72	2.42	0.1497	25.19	5.5	0.035	0.90	0.51
2000	27.1	2.59	7.92	25.68	2.42	0.1495	25.06	5.42	0.0345	1.61	0.90
2500	26.94	2.46	7.22	25.68	2.4	0.15	25.24	5.48	0.0345	2.50	1.41
3000	27.5	2.64	7.9	26.03	2.43	0.1484	25.38	5.56	0.035	3.68	2.07

SAMPLE	10										
V Volts	20 hz c uF	20 hz df %	20 hz esr Ω	1 khz c uF	1 khz df %	1 khz esr Ω	10khz c uF	10khz df %	10khz esr Ω	energy density (J/cc)	energy density (J/g)
0	24.34	1.29	4.21	23.68	1.54	0.1034	23.39	4.41	0.03	0.00	0.00
500	24.73	1.44	4.69	23.98	1.62	0.1076	23.66	4.52	0.0304	0.09	0.05
1000	26.82	2.41	7.04	25.58	2.43	0.1411	25.01	5.53	0.0354	0.40	0.22
1500	26.79	2.34	7.05	25.5	2.33	0.145	24.93	5.24	0.0335	0.90	0.50
2000	26.17	2.32	6.94	24.96	2.55	0.1643	24.38	5.93	0.0386	1.56	0.87
2500	27.11	2.59	7.23	25.63	2.45	0.1513	24.99	5.55	0.0354	2.52	1.41
3000	27.04	2.43	7.08	25.8	2.46	0.151	25.26	5.57	0.0352	3.62	2.03

SAMPLE	11										
V Volts	20 hz c uF	20 hz df %	20 hz esr Ω	1 khz c uF	1 khz df %	1 khz esr Ω	10khz c uF	10khz df %	10khz esr Ω	energy density (J/cc)	energy density (J/g)
20 VAC	24.34	1.26	4.12	23.71	1.49	0.1	23.42	4.3	0.0292		
500	24.67	1.38	4.42	23.97	1.61	0.107	23.7	4.51	0.0303	0.09	0.05
1000	26.94	2.45	7.16	25.52	2.42	0.1504	24.85	5.41	0.0346	0.40	0.22
1500	27.14	2.47	7.18	25.89	2.5	0.1531	25.36	5.64	0.0353	0.91	0.51
2000	27.2	2.53	7.32	25.72	2.41	0.1479	25.06	5.35	0.034	1.62	0.91
2500	27.06	2.44	7.13	25.83	2.45	0.1504	25.31	5.498	0.0343	2.52	1.41
3000	27.2	4.12	11.76	25.48	2.55	0.1585	24.86	5.43	0.0348	3.64	2.04

Steiner Caps		dtra				
D cap inch	D core inch	Height inch	total V cc	core V cc	Eff. V cc	MASS grams
1.32	0.38	1.5	33.621	2.7863	30.835	59.9

BATCH 2 uncoated

V Volts	20 hz c uF	20 hz df %	20 hz esr Ω	1 khz c uF	1 khz df %	1 khz esr Ω	10khz c uF	10khz df %	10khz esr Ω	energy density (J/cc)	energy density (J/g)
SAMPLE	**12**										
20 VAC	24.92	1.17	3.73	24.31	1.53	0.1003	24.04	5.36	0.0355		
500	25.41	1.35	4.22	24.7	1.63	0.105	24.39	5.33	0.0348	0.09	0.05

SAMPLE 14

V Volts	20 hz C uF	20 hz df %	20 hz esr Ω	1 khz c uF	1 khz df %	1 khz esr Ω	10khz c uF	10khz df %	10khz esr Ω	energy density (J/cc)	energy density (J/g)
20 VAC	25.2	1.19	3.77	24.57	1.44	0.073	24.34	4.52	0.0296		
500	25.7	1.37	4.24	24.99	1.6	0.102	24.71	4.73	0.0304	0.10	0.05
1000	28.4	2.54	6.99	26.87	2.48	0.1464	26.24	5.87	0.0355	0.42	0.24
1350	29.1	8.62	23.1	27.24	2.81	0.1617	26.7	5.91	0.0351	0.79	0.44

SAMPLE 15

V Volts	20 hz C Uf	20 hz df %	20 hz esr Ω	1 khz c uF	1 khz df %	1 khz esr Ω	10khz c uF	10khz df %	10khz esr Ω	energy density (J/cc)	energy density (J/g)
20 VAC	25.2	1.17	3.73	24.62	1.45	0.0935	24.37	4.6	0.03		
500	25.7	1.36	4.18	25.03	1.6	0.1017	24.77	4.79	0.0306	0.10	0.05
1000	28.6	2.58	7.08	27.01	2.51	0.1472	26.32	5.87	0.0355	0.43	0.24
1500	28.8	2.54	6.96	27.46	2.59	0.1514	27.03	6.73	0.0387	0.96	0.54
2000	30.1	14.3	36.1	27.32	2.78	0.1614	26.58	5.74	0.0343	1.79	1.01

Steiner Caps **dtra**

D cap inch	D core Inch	Height inch	total V cc	core V cc	Eff. V cc	MASS grams
1.12	0.375	3.02	48.732	5.46311	43.269	79.54

date 12/12/2002

BATCH 3 coated

V Volts	20 hz c uF	20 hz df %	20 hz esr Ω	1 khz c uF	1 khz df %	1 khz esr Ω	10khz c uF	10khz df %	10khz esr Ω	energy density (J/cc)	energy density (J/g)

SAMPLE	16										
20 VAC	31.7	2.15	5.4	30.99	1.82	0.0937	30.93	9.98	0.0513		
500	32	1.22	3.03	31.23	1.88	0.096	31.18	10.2	0.0521	0.08	0.05
1000	33.9	1.7	3.94	32.91	2.34	0.1128	32.75	11.06	0.0537	0.35	0.21
1500	36.5	2.27	4.9	34.76	2.7	0.1232	34.18	11.76	0.0548	0.84	0.52
2000	37	2.15	4.6	35.69	2.73	0.1215	35.35	12.2	0.055	1.52	0.93
2500	37.3	4.46	4.44	36.74	1.79	0.7734	36.14	2.74	0.1201	2.39	1.47
3000	38.1	2.15	4.46	36.64	2.79	0.1221	36.51	12.8	0.0561	3.52	2.16
3500	40.6	2.52	4.86	38.36	3.1	0.1283	37.62	14.27	0.0604	5.10	3.13
4000	41.9	2.47	4.63	40.13	3.75	0.1487	39.72	19.06	0.0764	6.88	4.21
4500	28.4	5.47	15.34	27.17	4.65	2.724	19.95	44.97	0.2985	5.90	3.62

SAMPLE	17		BATCH	3 coated						(J/cc)	(J/g)
	20 hz	20 hz	20 hz	1 khz	1 khz	1 khz	10khz	10khz	10khz	energy density	energy density
V	c	df	esr	c	df	esr	c	df	esr	y	y
Volts	uF	%	Ω	uF	%	Ω	uF	%	Ω	(J/cc)	(J/g)
20 VAC	32.3	1.15	2.84	31.56	1.96	0.099	31.14	11.5	0.058		
500	32.4	1.2	2.94	31.71	2.06	0.1031	31.61	11.68	0.0588	0.08	0.05
1000	34.3	1.65	3.83	33.26	2.48	0.1184	33.05	12.51	0.0602	0.35	0.22
2000	37.8	2.32	4.8	35.8	2.9	0.1286	35.05	13.69	0.0622	1.55	0.95
3000	38.4	2.37	4.66	38.6	3.27	0.1349	38.51	16.72	0.0695	3.55	2.17
4000	7.55	13.01	137.2	6.38	9.11	2.27	5.6	34.3	0.9761	1.24	0.76

SAMPLE	19		BATCH	3 coated						(J/cc)	(J/g)
	20 hz	20 hz	20 hz	1 khz	1 khz	1 khz	10khz	10khz	10khz	energy density	energy density
V	c	df	esr	c	df	esr	c	df	esr	y	y
Volts	uF	%	Ω	uF	%	Ω	uF	%	Ω	(J/cc)	(J/g)
20 VAC	33.26	1.15	2.74	32.56	2	0.0976	32.51	11.49	0.0563		
500	33.75	1.25	2.95	32.92	2.09	0.1007	32.79	11.6	0.0563	0.09	0.05
1000	36.35	1.92	4.17	34.92	2.63	0.1195	34.55	12.47	0.0575	0.37	0.23
2000	39.46	2.42	4.79	37.34	2.88	0.1226	36.47	13.36	0.0584	1.62	0.99
3000	40.93	2.47	4.73	38.72	3.1	0.1272	37.72	15.01	0.0634	3.78	2.32
3500	43.26	2.62	4.75	40.89	4.21	0.1638	39.54	24.38	0.0982	5.44	3.33
4000	40.2	9.16	18.11	35.51	7.662	0.3414	32.23	39.9	0.1972	6.60	4.04
4100	37.11	6.03	12.87	33.43	10.77	0.5131	28.75	51.12	0.2832	6.40	3.92
4200	0.254	7.36	2290	0.21	8.38	63.4	0.186	18.11	15.5	0.05	0.03

SAMPLE	20		BATCH	3 coated						(J/cc)	(J/g)
	20 hz	20 hz	20 hz	1 khz	1 khz	1 khz	10khz	10khz	10khz	energy density	energy density
V	c	df	esr	c	df	esr	c	df	esr	y	y
Volts	uF	%	Ω	uF	%	Ω	uF	%	Ω	(J/cc)	(J/g)

20 VAC	32.25	1.13	2.8	31.57	1.98	0.0999	31.25	11.36	0.0578		
500	32.76	1.25	3.02	31.96	2.09	0.1039	31.78	11.82	0.0592	0.08	0.05
1000	35.21	1.89	4.23	33.8	2.57	0.1206	33.14	12.39	0.0595	0.36	0.22
2000	38.01	2.32	4.76	35.97	2.83	0.125	34.97	13.33	0.0607	1.56	0.96
3500	34.94	14.27	34.98	25.65	8.07	0.5014	23.6	33.98	0.2293	4.39	2.69
4000	23.34	24.39	83.4	16.58	11.86	1.14	14.29	46.96	0.5235	3.83	2.35

SAMPLE	21		BATCH	3 coated						(J/cc)	(J/g)
	20 hz	20 hz	20 hz	1 khz	1 khz	1 khz	10khz	10khz	10khz	energy density	energy density
V	c	df	esr	c	df	esr	c	df	esr		
Volts	uF	%	Ω	uF	%	Ω	uF	%	Ω	(J/cc)	(J/g)
20 VAC	33.11	1.15	2.76	32.41	1.93	0.0948	32.3	10.99	0.0542		
500	33.56	1.25	2.96	32.75	1.98	0.0964	32.46	10.85	0.0532	0.09	0.05
1000	35.77	1.81	4.01	34.47	2.45	0.1132	33.92	11.61	0.0545	0.37	0.22
2000	39.03	2.39	4.77	36.92	2.8	0.1206	35.91	12.62	0.056	1.60	0.98
3000	41.93	2.56	4.8	39.72	3.27	0.1311	38.66	16.47	0.0679	3.87	2.37
3500	43.82	2.76	4.92	41.29	4.89	0.1885	39.56	29.95	0.1206	5.51	3.37
4000	32.58	3.32	8.04	29.59	9.15	0.494	25.45	40.36	0.2525	5.35	3.28

SAMPLE	22		BATCH	3 coated						(J/cc)	(J/g)
	20 hz	20 hz	20 hz	1 khz	1 khz	1 khz	10khz	10khz	10khz	energy density	energy density
V	c	df	esr	c	df	esr	c	df	esr		
Volts	uF	%	Ω	uF	%	Ω	uF	%	Ω	(J/cc)	(J/g)
20 VAC	33.13	1.16	2.77	32.41	1.91	0.0939	32.02	10.33	0.0513		
500	33.6	1.27	3	32.76	2.04	0.0989	32.53	10.86	0.0531	0.09	0.05
1000	36.43	2.01	4.37	34.94	2.61	0.1188	34.28	11.65	0.0541	0.37	0.23
1500	38.69	2.47	4.98	36.55	2.81	0.1221	35.54	12.08	0.0541	0.89	0.55
2000	40.32	2.56	4.97	38.06	2.83	0.1182	37.06	12.45	0.0535	1.65	1.01
2500	42.46	2.75	5.05	40.09	3.03	0.1198	39.09	14.19	0.0578	2.72	1.67
3000	43.46	2.73	4.94	41.02	3.29	0.1275	40.01	16.12	0.0641	4.01	2.46
3200	44.16	2.74	4.87	41.68	3.48	0.1373	40.62	17.6	0.069	4.64	2.84
3500	45.25	2.86	4.96	42.59	3.85	0.1438	41.36	20.48	0.0789	5.69	3.48
3600	45.94	2.96	5.07	43.15	4.21	0.1553	41.92	23.07	0.0876	6.11	3.74
3700	18.98	4.58	19.21	15.84	24.36	2.45	11.95	80.2	1.068	2.67	1.63

SAMPLE	29		BATCH	3 coated						(J/cc)	(J/g)
	20 hz	20 hz	20 hz	1 khz	1 khz	1 khz	10khz	10khz	10khz	energy density	energy density
V	c	df	esr	c	df	esr	c	df	esr		
Volts	uF	%	Ω	uF	%	Ω	uF	%	Ω	(J/cc)	(J/g)
20 VAC	32.37	1.22	3	31.59	6.21	0.3131	30.63	47.96	0.2492		
500	32.85	1.33	3.21	31.96	6.37	0.3174	31.08	48.92	0.2505	0.08	0.05
1000	35.56	1.96	4.35	34.05	7.19	0.3358	32.64	51.87	0.253	0.36	0.22

2000	38.29	2.47	5.08	35.99	7.82	0.3462	34.2	55.52	0.2585	1.57	0.96
2500	38.47	2.45	4.94	36.35	8	0.3503	34.45	56.77	0.2625	2.47	1.51
3000	38.98	2.51	5.05	36.8	8.39	0.3627	34.79	59.64	0.273	3.60	2.21
3500	40.43	2.63	5.11	38.15	9.65	0.4025	35.76	69.75	0.3106	5.08	3.11
4000	41.99	2.68	4.99	39.55	11.53	0.464	36.59	85.51	0.3721	6.89	4.22

SAMPLE	30		BATCH	3 coated						(J/cc)	(J/g)
	20 hz	20 hz	20 hz	1 khz	1 khz	1 khz	10khz	10khz	10khz	energy density	energy density
V	c	df	esr	c	df	esr	c	df	esr		
Volts	uF	%	Ω	uF	%	Ω	uF	%	Ω	(J/cc)	(J/g)
20 VAC	31.29	1.13	2.87	30.64	1.82	0.0944	30.36	9.76	0.0511		
500	31.51	1.17	2.94	30.82	1.85	0.0953	30.54	9.83	0.0512	0.08	0.05
1000	33.71	1.79	4.17	32.46	2.3	0.1128	31.91	10.54	0.0525	0.35	0.21
2000	36.76	2.39	5.05	34.79	2.68	0.1223	33.8	11.37	0.0536	1.51	0.92
2500	37.36	2.4	5.07	35.24	2.72	0.1228	34.22	11.54	0.0537	2.40	1.47
3000	37.4	2.32	4.87	35.59	2.74	0.1223	34.62	11.81	0.0543	3.45	2.12
3500	38.26	2.35	4.82	36.38	2.94	0.1286	35.39	13.36	0.0601	4.81	2.95
4000	39.46	2.44	4.83	37.42	3.47	0.1473	36.32	7.38	0.0762	6.48	3.97

Steiner Caps		dtra				
D cap	D core	Height	total V	core V	Eff. V	MASS
inch	inch	inch	cc	cc	cc	grams
1.12	0.375	3.02	48.732	5.4631	43.27	70.51

date 12/12/3002

BATCH 4 uncoated

SAMPLE	24										
	20 hz	20 hz	20 hz	1 khz	1 khz	1 khz	10khz	10khz	10khz	energy	energy
V	c	df	esr	c	df	esr	c	df	esr	density	density
Volts	uF	%	Ω	uF	%	Ω	uF	%	Ω	(J/cc)	(J/g)
20 VAC	33.94	1.16	2.72	33.19	3.12	0.1494	32.86	21.7	0.1051		
500	34.56	1.31	3.01	33.64	3.23	0.1529	33.32	22.09	0.1055	0.09	0.06

SAMPLE	25										
	20 hz	20 hz	20 hz	1 khz	1 khz	1 khz	10khz	10khz	10khz	energy	energy
V	c	df	esr	c	df	esr	c	df	esr	density	density
Volts	uF	%	Ω	uF	%	Ω	uF	%	Ω	(J/cc)	(J/g)
20 VAC	33.73	1.15	2.72	33.01	2.84	0.1368	32.72	19.82	0.0964		
500	34.35	1.3	2.99	33.46	2.96	0.1407	33.23	20.24	0.097	0.09	0.06
1000	35.4	1.67	3.73	34.3	3.3	0.1525	32.31	20.76	0.0981	0.36	0.25

SAMPLE	26

V Volts	20 hz c uF	20 hz df %	20 hz esr Ω	1 khz c uF	1 khz df %	1 khz esr Ω	10khz c uF	10khz df %	10khz esr Ω	energy density (J/cc)	energy density (J/g)
20 VAC	33.95	7.3	17.09	33.04	3.24	0.1558	32.61	21.44	0.1046		
500	34.37	1.31	3.03	33.46	3.24	0.154	33.04	21.73	0.1047	0.09	0.06
700	35.21	1.52	3.39	34.04	3.37	0.1569	33.68	22.36	0.1057	0.18	0.12
800	35.88	1.69	3.71	34.59	3.46	0.1593	34.05	22.6	0.1056	0.24	0.16
900	36.69	1.92	4.08	35.15	3.64	0.1648	34.6	23.11	0.1063	0.30	0.21

SAMPLE	27									(J/cc)	(J/g)
V Volts	20 hz c uF	20 hz df %	20 hz esr Ω	1 khz c uF	1 khz df %	1 khz esr Ω	10khz c uF	10khz df %	10khz esr Ω	energy density (J/cc)	energy density (J/g)
20 VAC	34.64	1.25	2.87	33.75	4.87	0.2297	33.26	38.4	0.1838		
500	35.02	1.33	3.02	34.12	4.91	0.2289	33.55	38.67	0.1834	0.09	0.06
										0.00	0.00

SAMPLE	28										
V Volts	20 hz c uF	20 hz df %	20 hz esr Ω	1 khz c uF	1 khz df %	1 khz esr Ω	10khz c uF	10khz df %	10khz esr Ω	energy density (J/cc)	energy density (J/g)
20 VAC	34.13	1.65	0.1645	32.55	4.26	0.2081	32.13	30.07	0.149		0.00
500	34.26	1.71	39.67	32.6	4.26	0.208	32.16	30.06	0.1487	0.09	0.06

A summary of average values for the energy densities in the capacitors of Batch 1, 2, 3, and 4 is shown in the Table 33 .

Table 33 Maximum Energy density in PVDF caps. Active electrode: 10 Ohms/sq. Heavy Edge: 2 Ohms/sq. PVDF film: 8 microns. No segmentation.

Capacitor Series	Coated	Film Width (inch)	Energy (J/cc)	Energy (J/g)
B1	Yes	1.5	4.30	2.42
B2	No	1.5	1.79	1.01
B3	Yes	3.0	6.89	4.22
B4	No	3.0	0.36	0.25

The results in Table 33 show that a record energy density (6.89 J/cc) has been established in acrylated PVDF films capacitors.

APPENDIX A
PVDF AND PET FILM

SUPPLIERS.

The main suppliers for PVDF have been identified as TERPHANE (US) and KREHA (JAPAN). We found out that KREHA prices, delivery time, and flexibility are inadequate for our purposes in this project. We have chosen to order PVDF film fro TERPHANE at the following address:

TERPHANE
2754 W Park Ave Bloomfield NY 14489
Phone: 716-657-5800

Thickness available for thinnest films: 4.5μ and 8μ films . The film characteristics as supplied by TERPHANE are shown in Table A1.

Table 1. Characteristics of PVDF Film supplied by Terphane.

Thickness	**μm**		4.5	5	8	15
Tensile Stength	**Mpa**	MD	199	195	190	188
		TD	230	219	247	257
Elongation @ break	**%**	MD	96	99	103	130
		TD	38	41	50	56
Modulus	**Mpa**	MD	1365	1683	2292	2469
		TD	1145	1273	2106	2284
Force @ 5% Elongation	**Mpa**	MD	61	60	60	58
		TD	58	56	55	51
Dimensional Stability 150 deg. C, 30 min	**% Change**	MD	-10.6	-9.6	-9.4	-8.3
		TD	-7.3	-5.5	-8.6	-9.1
Dimensional Stability 120 deg. C, 30 min	**% Change**	MD	-5.3	-4.4	-4.8	-4.7
		TD	-1.9	-1.5	-3.2	-3.6
Density	**g/cm3**		1.8	1.8	1.8	1.8
Water Absorption	**%**		<.04	<.04	<.04	<.04
Surface Resistance	**Ohms**		>=10^14	>=10^14	>=10^14	>=10^14
Volume Resistivity	**Ohm-cm**		>=10^14	>=10^14	>=10^14	>=10^14
Dielectric Constant	**21C, 1.3kHz**		10.9	10.9	10.9	10.9
Dielectric Loss	**21C, 1.3kHz**		0.16	0.16	0.16	0.16
Breakdown Voltage	**VDC/μm**		377-455	456	535-590	>400
Crystal Melting Temperature	**Deg. C**		175	175	175	175

Suppliers of PET film have been identified as DUPONT FILM, TORAY, and TERPHANE. Data supplied by Dupont (of Circle Ville Ohio, Phone: 800-395-0961) on 1.2 and 1.4 μm PET (Mylar) film is shown in Table A2.

Table 2. Specific Properties of 1.2 and 1.4 μm thick Mylar (Polyester) Film by Dupont

PROPERTY	UNIT	TYPICAL VALUE		TEST METHOD
FILM THICKNESS	**μm**	1.2	1.4	ROLL WEIGHT
MODULUS				
MD	**N/mm^2**	4200		ASTM D-882
TD		4800		
TENS. STRENGTH				
MD	**N/mm^2**	170		ASTM D-882
TD		200		
ELONGATION				
MD	**%**	60	65	ASTM D-882
TD		40	45	
HEAT SHRINKAGE				
MD	**%**	2.0	2.1	150 °C, 30 min
TD		1.0	1.1	
DIELECTRIC STRENGTH	**V**	160	210	0.5 μF Film/ Roll Units
DIELECTRIC CONSTANT		3.25		ASTM D-150

APPENDIX B
ELECTRODE SEGMENTATION ROLLER SUPPLIERS

The following companies can fabricate custom print rollers:

1. Bolmet
Phone: 860-774-7431
Att: Philippe Jaspart

2. AD Tech
Phone: 800-767-5432
Att: Mr Glen Walters

3. Bingham of Arizona
Phone 602-268-4492
Att Richard Drevs.

APPENDIX C
METALLIZATION COMPANIES

A listing of metallization companies is shown in Table 3.

Table 3. List of selected metallization companies around the world.

Vacuum Depositing Inc. 1294 Old Fern Valley Road Louisville, KY 40219-1903 (Contact: Al Ploetner)	American Thin Films 2010 East Hennepin Ave. Minneapolis, MN 55413	Vapor Technologies Inc. Boulder Tech Center P.O. Box 11170 Boulder, CO 80301
NeoVac Inc. 980-B Airway Ct. Santa Rosa, CA 95403	Thelamco Inc. 1202 Territorial Rd P.O. Box 456 Benton Harbor, MI 49023	CPFilms Inc. P.O. Box 5068 Martinsville, VA 24115-5068
Filmquest Inc. 3820 Ohio Ave. Suite 12 St. Charles, Il. 60174-5463	Kaisers International Corp. 7th FL., 23 Chang An East Rd, Sec. 1 Taipei, Taiwan	Douglas-Hanson Co. 1060 Clyde Hanson Dr. Hammond, WI 54015-0528
Dunmore Corporation 207 Penns Trail Newtown, PA 18940-1816	Foilmark Inc. 5 Malcolm Hoyt Dr. Newburyport, MA 01950-4082	Metallized Products Inc. 37 East St. Winchester, MA 01890-1198
Mylan Technologies Inc. 110 Lake St. St. Albans, VT 05478-2287	SKC America Inc/Film Div. 850 Clark Dr. Budd Lake, NJ 07828-4303	Advanced Web Products Inc. 218 Newgate Rd. East Granby, CT 06026-9557
Artus Corporation 201 South Dean St. P.O. Box 511 Englewood, NJ 07631-0511	CastCal 2285 West County Road C St. Paul, MN 55113-2567	Advanced Deposition Technologies Myles Standish Industrial Park Taunton, MA 02780
Alcan Deutschland GmbH Koelner Strasse 8, Postfach 5149 D-65726 Eschborn, Germany	Les Industries Alubec Inc. 417 Place de Louvain Montréal, Québec H2N 1A1	AEP Performance 351 Holt Rd. North Andover, MA 01845-1046
Catalina Plastics & Coatings 27001 Agoura Road Calabasas Hills, CA 91301-5339	Celplast Metallized Products 67 Commander Blvd. Scarborough, Ontario M1S 3M7	Chamberlain Plastics Ltd. North End Higham Ferrers Northamts UK NN108JD
Chantler Packaging Inc. 880 Lakeshore Road E. Mississauga, Ontario L5E 1E1	Coburn Corp. 1650 Corporation Road West Lakewood, NJ 08701-5974	Darly Custom Technology, Inc. 121 West Dudley Town Rd. Bloomfield, CT 06002
Dri-Print Foils 329 New Brunswick Ave. Rahway, NJ 07065-2997	Elviomet Paper & Plastic Metallizing Industrial Area of Komotini P.O. Box 50 Komotini, Greece GR-69100	Fabrico/Electrical Insulation WI 10436 North Port Washington Road Mequon, WI 53092-5535

Table C-1 (Cont.). List of selected metallization companies around the world

Comcographics 116 Queenstown St. Devuns, MA 01432-4408	Comcographics Inc. 1741 Woodhaven Dr. Belsalem, PA 19020-7107	Creative Coatings Corp. 28 Charron Ave P.O. Box 1165 Nashua, N.H. 03061-1165
Crown Roll Leaf, Inc. 91 Illinois Ave Paterson, NJ 07503-1722	Glitterwrap Inc. 701 Ford Road Rockway, NJ 07866-2047	Gomar-National Industries 1501 W. Blancke St. Linden, NJ 07036
Grafix Plastics 19499 Miles Rd. Cleveland, OH 44128	Fibre Leather Manufacturing Corp. 686 Belleville Ave New Bedford, MA 02745	Filmet Via Baschenis 1 Milan, Italy I-20157
FLEXcon 1 Flexcon Industrial Park Spencer, MA 01562-2642	Galileo Vacuum Systems, Inc. Box 1158 East Granby, CT 06026	

APPENDIX D
CAPACITOR ENCAPSULATION

In some instances, the capacitors will require an outer protection from incidental damage. Two types of coatings have been tested, **epoxies** and **silicones**. In general, the epoxies are harder and provide a more rigid and robust coating and will prevent damage from mechanical contact. The silicones are more impervious to water and oxygen transport and will provide better protection from environmental contamination. The best coating may be a double layer coating.

Several samples with different chemistries and curing conditions were prepared. Some samples were prepared with two layer coatings. The samples were inspected for uniformity of the coating and for completeness of the cure based on the tackiness. The different materials used are described in Table I.

The best epoxy coating found so far was **Material F**. The best silicone coating was **Material A**. For the two layer coatings, the epoxy compounds coated the silicone base very poorly, but the silicone over the epoxy had much better results.

Table 4. Potting/Encapsulation Materials

Material ID	Material Name	Producer	Material Type
A	Sligard 184	Dow Corning	Clear Two Part Silicone
B	Silastic J	Dow Corning	Green Two Part Silicone
C	Compound CC3-402 Hardener H7	Cast - Coat, Inc.	Black Two Part Epoxy
D	Compound CC3-402 Hardener H34	Cast - Coat, Inc.	Black Two Part Epoxy
E	Compound CC3-301AD Hardener H7	Cast - Coat, Inc.	Black Two Part Epoxy
F	Compound CC3-301AD Hardener H34	Cast - Coat, Inc.	Black Two Part Epoxy
G	Epo-tek 600-2	Epoxy Technology	Tan One Part Epoxy
H	Epo-tek 77	Epoxy Technology	White Two Part Epoxy

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